# Structural Interpretation of Ordovician Mafic Dike Swarms, Transantarctic Mountains, Southern Victoria Land, Antarctica

A Thesis
presented in partial fulfillment
of the requirements for the
Degree of Bachelor of Science.

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by
Robert J. Janosy

Department of Geological Sciences
The Ohio State University

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Approved by

Terry J. Wilson
Advisor

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# INTRODUCTION

The Transantarctic Mountains traverses approximately 5000 km. across the Antarctic continent from northern Victoria Land to the Weddell Sea (Fig. 1). It consists of a Precambrian to Ordovician metasedimentary and igneous basement complex overlain unconformably by relatively flat-lying Devonian to Triassic sedimentary rocks of the Beacon Supergroup. The varied igneous rock types of the basement complex, consisting of granitoids and mafic dike swarms, were named the 'Granite Harbour Intrusive Complex' by Gunn and Warren (1962). Uplift and erosion of the basement complex resulted in formation of the Kukri Peneplain unconformity surface. Subsequent subsidence and deposition of sedimentary strata of the Beacon Supergroup followed. Thick and extensive Jurassic dolerite bodies (Ferrar Dolerite) intrude the basement complex and Beacon Supergroup. Uplift of the present mountain range is related to rifting in the Mesozoic and Cenozoic.

The Ross orogen developed along the margin of the East Antarctic craton, traversing the entire length of the Transantarctic Mountains. This Cambro-Ordovician orogen was characterized by deformation and metamorphism of metasedimentary basement sequences of the 'Ross System' and widespread magmatism. Intruding granitoids of the basement complex, defined by Gunn and Warren (1962) as the 'Granite Harbour Intrusive Complex,' reflect radiometric ages similar to that of the Ross Orogeny. These granitoids occur as both deformed and undeformed in character with the deformed type showing a uniform style of foliation (Borg, 1983).

Recent tectonic interpretations regarding the evolution of the Ross orogen propose westward dipping subduction beneath the margin of the East Antarctic craton (Fig. 2) (Borg et al, 1990). Evidence of some mantle-derived magmas along with crustal melts generated by subducting oceanic lithosphere are observed in Early Paleozoic granitic plutons (Fig. 3). Additional supporting evidence stems from an inferred suture of an allochthonous Beardmore Microcontinent (a possible far-travelled terrane) with the margin of the East Antarctic Craton during

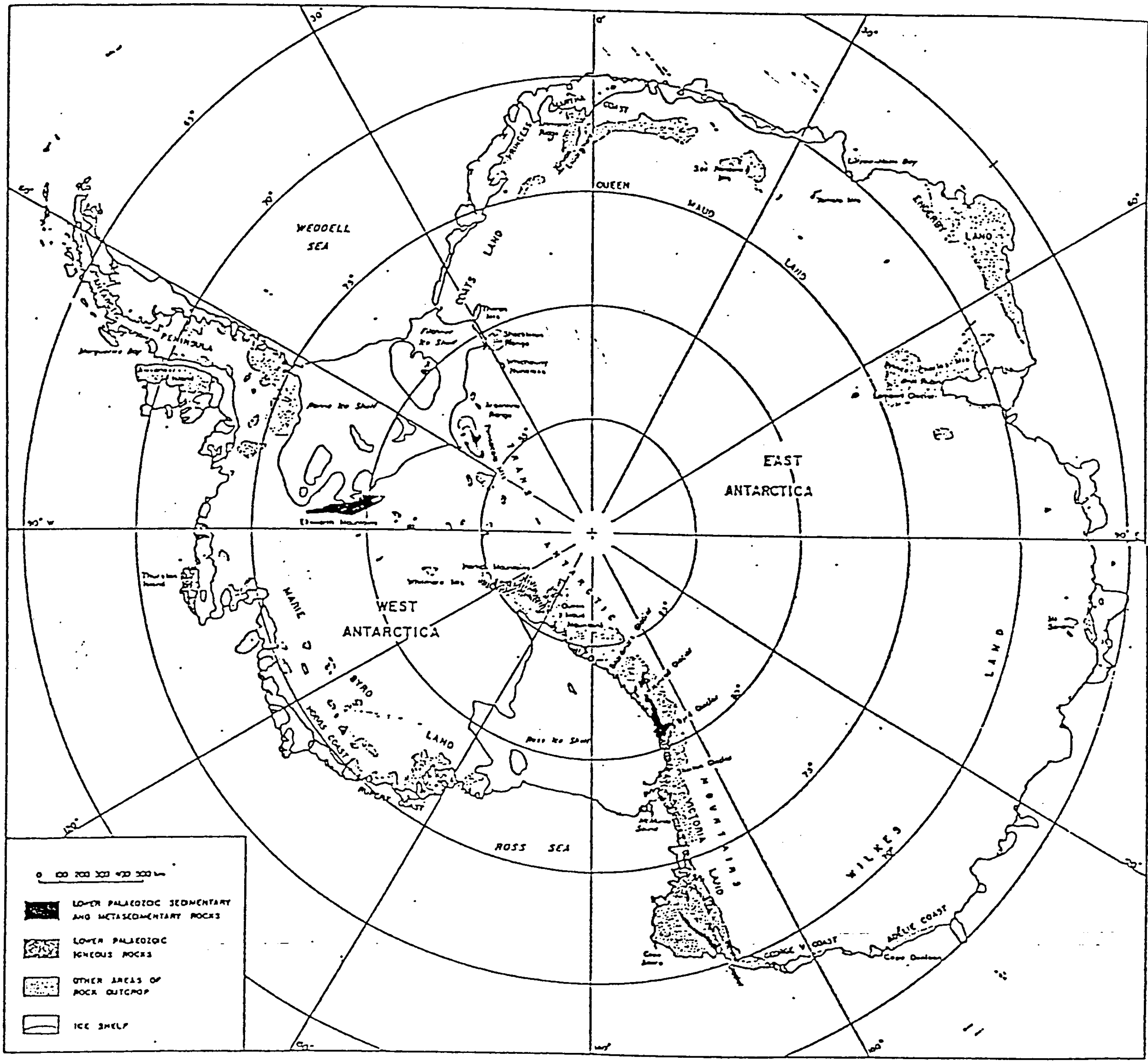



FIG. 1. Map of Antarctica showing distribution of Lower Palaeozoic rocks.

(after Laird in Holland (ed), 1981, fig. 1)

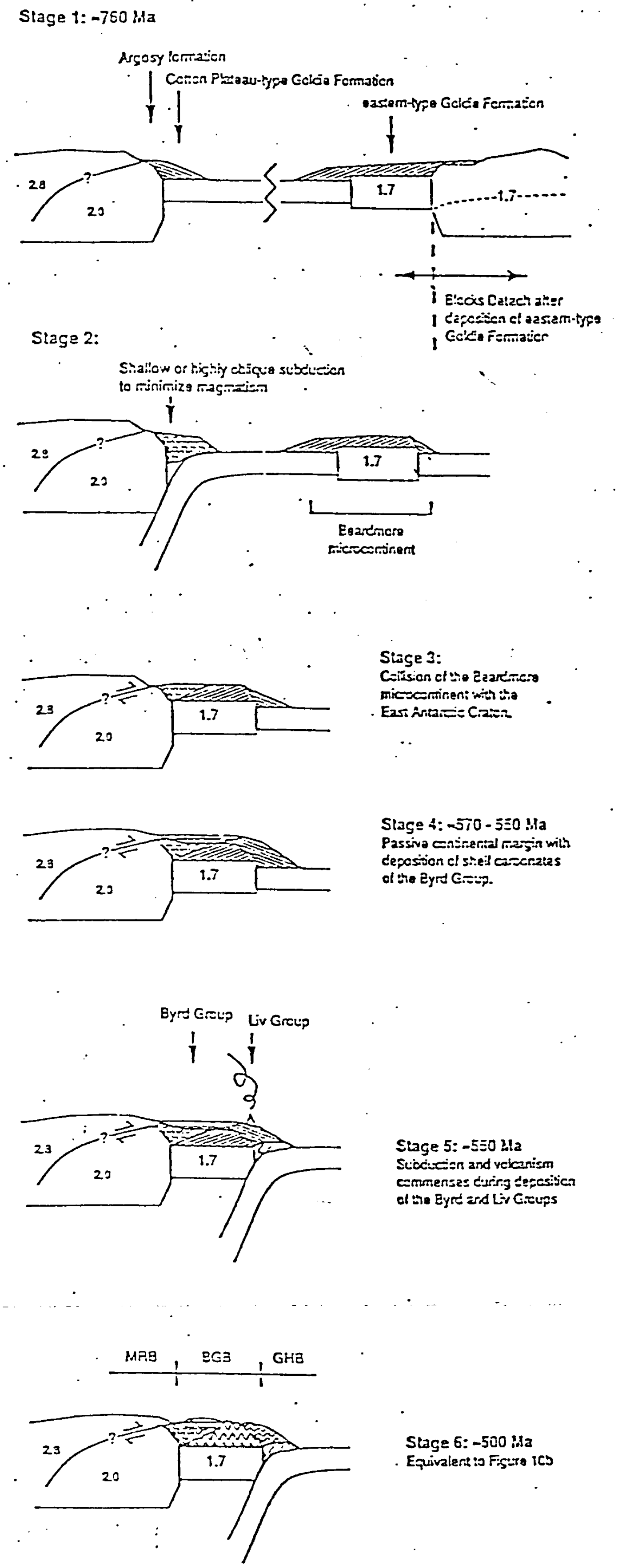



Figure 2. Composite cross-sectional sketches illustrating a tectonic model for the development of the central Transantarctic Mountains from ~760 Ma through emplacement of the ~500 Ma granites.

(after Borg, 1990, fig. 11)

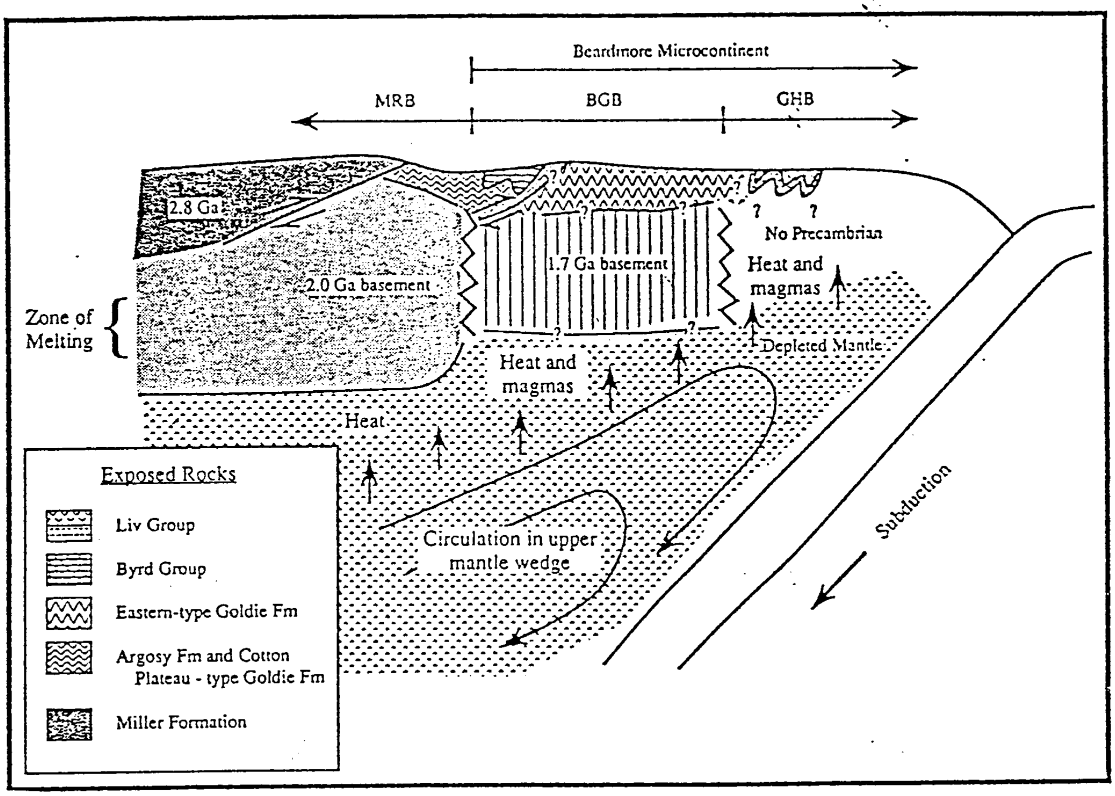



Figure 3. Composite cross-sectional sketch illustrating the crustal structure and tectonic setting inferred for the central Transantarctic Mountains after folding of the Ross Orogeny and during emplacement of the ~500 Ma granites.

(after Borg, 1990, fig. 10b)

subduction (Borg et al 1990). Accretion of allochthonous terranes through strike-slip translation (of several hundred kilometers) has also been postulated for development of the East Antarctic margin (Rowell & Rees, 1989). Evidence of juxtaposition of a Middle and Upper Cambrian volcanic-rich outboard terrane against a Lower Cambrian thick carbonate inner terrane (with unconformably overlying clastics) support this model (Fig. 4). The time of emplacement of the outboard terrane is restricted to after depostion of the Cambrian Shackleton Limestone and prior to deposition of basal Devonian beds of the Beacon Supergroup. Age uncertainty, problematic constraints of volcanic emplacement, and understanding of facies patterns of the Lower Cambrian rocks, however, still creates a need for further investigation of this proposed model.

Initial geological explorations of Antarctica (Ferrar, 1907; Prior, 1907; Mawson, 1916; Smith, 1924) noted the occurrences of mafic dike swarms in regions of southern Victoria Land near Terra Nova Bay, Granite Harbour, and the Ferrar and Blue Glaciers. Subsequent schematic mapping and petrological observations of these mafic dikes throughout these regions were presented by McKelvey and Webb (1962), Blank et al. (1963), and Haskell et al. (1965).

In this study I will document the regional extent and orientation of mafic dike swarms of southern Victoria Land through a compilation from both these previously noted occurrences and recently acquired systematic measurements from Granite Harbour (Wilson unpublished, 1989). In addition, I discuss the use of dikes as structural and tectonic markers and present interpretations regarding the tectonic setting of the region during dike swarm emplacement in relation to recently proposed models for the Ross Orogeny.

## DIKES AS STRUCTURAL AND TECTONIC MARKERS

### Dikes as Tensile Hydrofractures

Hydrofractures represent fluid-induced dilational cracks which parallel the plane containing the maximum compressive stresses and are oriented normal to least compressive stresses. Dikes

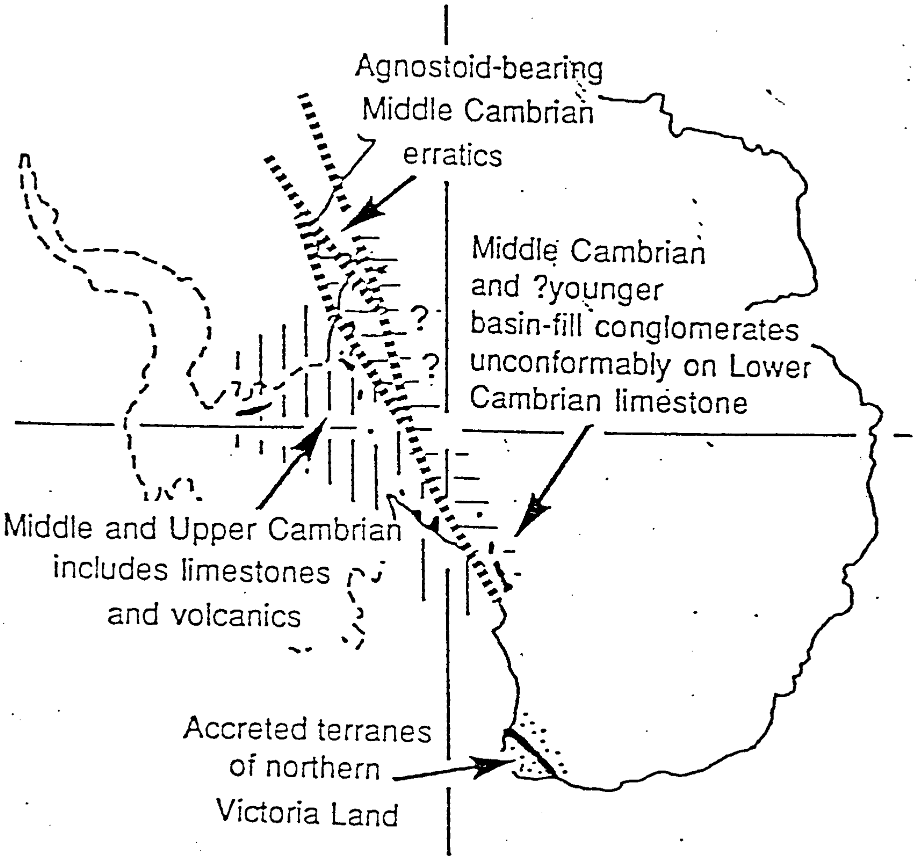



Figure 4. Principal terranes of the central and western Transantarctic Mountains. Terrane boundaries shown by heavy broken line. Inboard sequence ornamented by horizontal lines; outboard terrane, which is probably composite, ornamented by vertical lines. Principal characteristics of Middle and Upper Cambrian rocks emphasized. (after Rowell and Reese, 1989, fig. 7)

also are depicted as hydrofractures since intruding magma will propagate in a plane normal to the least compressive stresses (Fig. 5). The intruding magma must exert a higher magma pressure (hydraulic) than that of the minimum compressive stress in order to propagate and generate tension in the host rock. Dike propagation occurs at the fracture tip where extensional stresses are greatest and where tensile fractures originate (process zone). After tensile fractures form, advancing magma will subsequently invade them (Fig. 6).

Instead of propagating a new hydrofracture, magma can invade crustal zones of weakness such as pre-existing faults and joints. Delaney et al. (1986) identified three scales of joint occurrences which refer to increasing horizontal extent away from the dike margin. Adjacent joints were described as forming for a distance away from the dike, typically one percent of the dike's outcrop length. Local joints are present at a distance comparable to the dikes outcrop length, and regional joints occur over distances greater than the dike's length (typically > 3 km). One can infer the mechanics of dike emplacement based on the presence or absence of these types of joints in the host rocks. If dike-parallel adjacent joints are absent at an outcrop but dike-parallel regional joints are present, it could be inferred that the dike may have intruded into older joints. Criteria that may be helpful in recognizing this structural control would include cross-cutting relationships such as joints terminating at dike margins, indicating dikes intruded into pre-existing joints. Synchronous emplacement would display joints cutting into the dike. Shear displacement across a dike would indicate it's response to stresses acting from a direction different than that of the joint's orientation. Dike splays at the tip of the pre-existing fracture record that dilation and propagation involved a shift in direction in response to a resolved shear stress. Pre-existing joints may also be recognized if there are no joints in the host rocks that are of comprable dimensions to that of the dikes, signifying that dikes propagated their own fractures.

Delaney et al. (1986) described the basis for using dikes for paleostress analysis. If dikes have different strikes and are the same age, they are either 1) indifferent to propagating in the direction of least compressive stresses and therefore controlled by pre-existing fracture trends or 2)

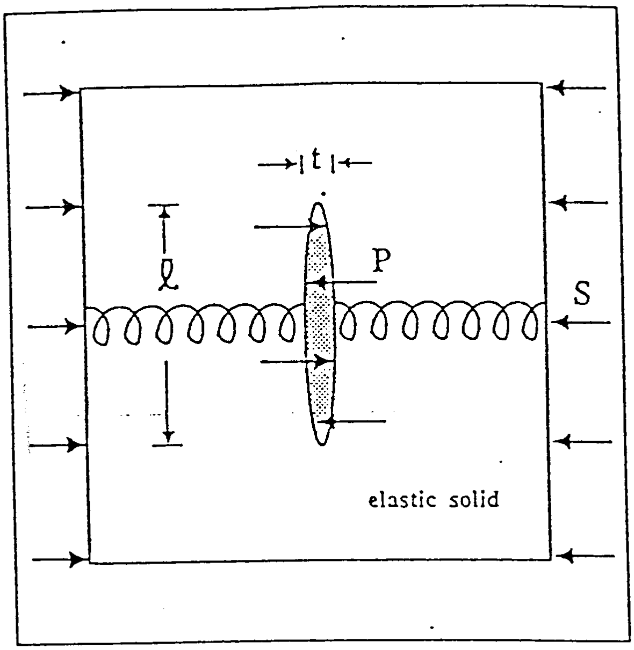



Figure 5. Schematic figure illustrating the structural interpretation of dykes. Magma driving pressure (difference between magma pressure, P, and remote compressive stress, S) is estimated from measurement of dyke thickness, t, dyke length, l, and elastic stiffness of the host rock (represented by the spring). (after Pollard <u>in</u> Halls (ed), 1987, fig. 1a)

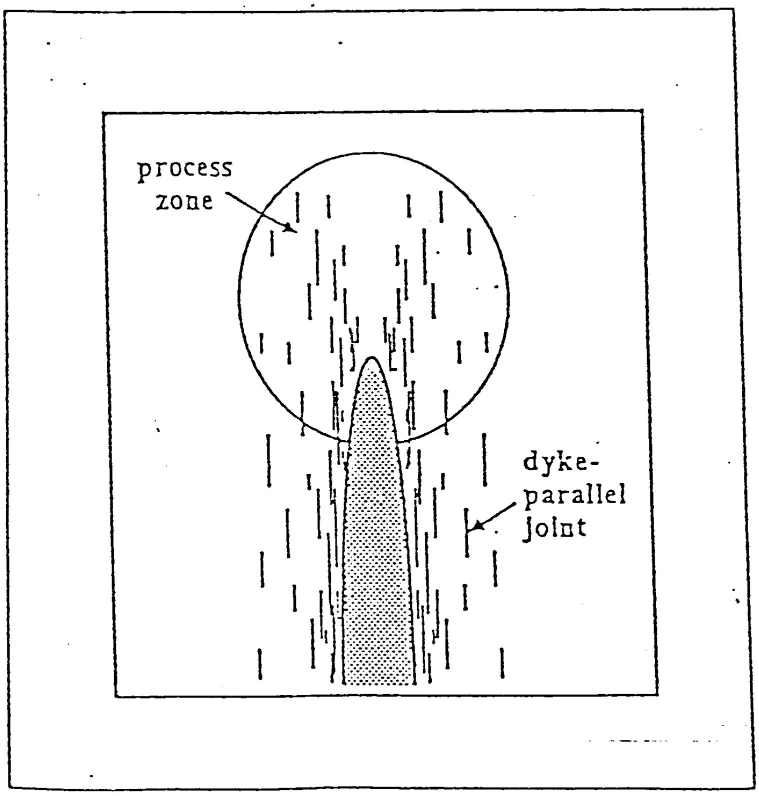



Figure 6. Schematic figure illustrating the structural interpretation of dykes. The propagation mechanism is identified from observations of structures such as joints close to the dyke contact and in the process zone at the dyke tip. (after Pollard in Halls (ed), 1987, fig. 1c)

experienced heterogeneous stresses. Dikes exhibiting these orientations are poor indicators of a paleostress direction. However, dikes displaying similar strikes occur because of a common tectonic element such as planes of weakness which they shared or due either to propagation as hydraulic fractures perpendicular to the least compressive stress direction.

Propagation paths and fracture mechanics of dikes can change during emplacement if there is a shift in the orientation of the least compressive stress. Pollard (1987) identified three modes of fracture associated with stress-controlled dike paths (Fig. 7). A Pure mode I fracture involves an ideal dike path in which fractures are induced by a homogeneous stress state with the least compressive stress acting normal to the dike plane. These fractures will produce simple planar sheets. When the state of stress changes and the least compressive stress changes orientation through rotation about an axis parallel to the dike periphery, a mixed mode I, II fracture is produced. If propagation and loading of the mixed mode I,II model is continuous and gradual, the dike tip will follow a smooth curved path. The third model, the mixed mode I, III fracture involves fracturing where rotation of the least compressive stress occurs about an axis parallel to the dike's propagation direction. The net effect is a series of segments at the dike's tip which individually propagate and twist to reorient normal to local least compressive stresses. The plan view of these oblique fractures exhibits an en echelon arrangement (providing stress reorganization is smooth and continuous) (Fig.8).

As tensile stresses generate fracturing openings, intruding magma will continue to enlarge the fracture through dilation. It has been commonly assumed that dilation occurs in a horizontal direction perpendicular to the trend of the dike. In addition, where primary field evidence of oblique dilation is observed, a common assumption is that the offset resulted from a horizontal shear component. Bussell (1989) describes the use of simple geometric techniques to accurately determine the true dilation direction of dikes. Where the dike walls step laterally, the two offset dike walls will form an offset plane with two offset edges (Fig. 9). If the trend and plunge of the offset edges can be measured in the field along with the azimuth of the line joining the offset edges,

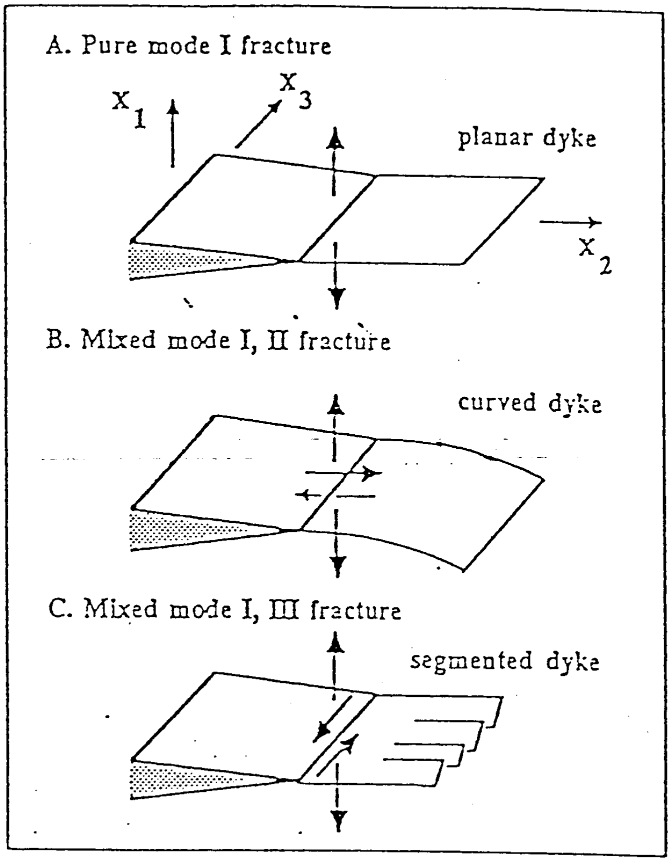



Figure 7. *Propagation paths for dykes related to the spatial change in orientation of the least compressive stress and the modes of fracture. A: Mode I fracture is induced by a least compressive stress acting perpendicular to the dyke plane and produces a planar dyke. B: Mixed mode I and I fracture is induced by a spatial rotation of the least compressive stress about an axis parallel to the dyke periphery This produces a curved dyke. C: Mixed mode I and III fracture is induced by a spatial rotation of the least compressiv stress about an axis parallel to the propagction direction This produces a segmented dyke.*

(after Pollard in Halls (ed), 1987, fig. 13).

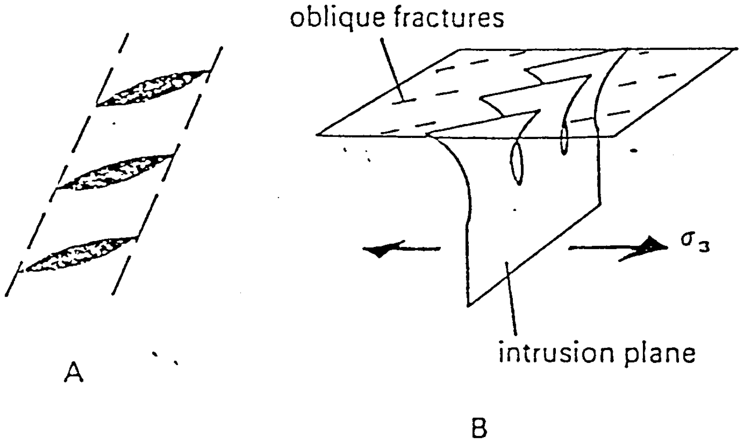



Figure 8. Explanation of en-echelon dykes by the filling of oblique fractures. *A*. Plan view of en-echelon dykes. *B*. How the en-echelon dykes may be related to a single intrusion plane at depth. (after Parks, 1989, fig. 11.4)

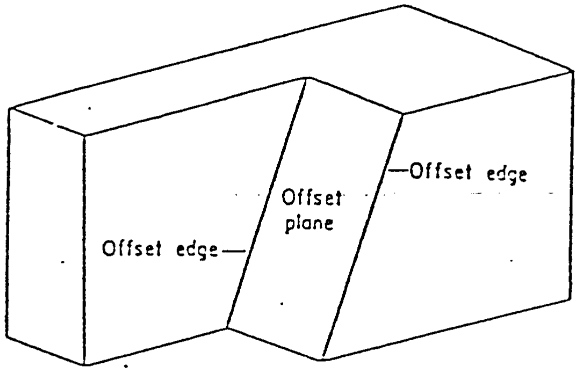



Figure 9. Sketch showing the intersection of a dyke wall with an offset plane to form an offset edge. (after Bussell, 1989, fig. 3)

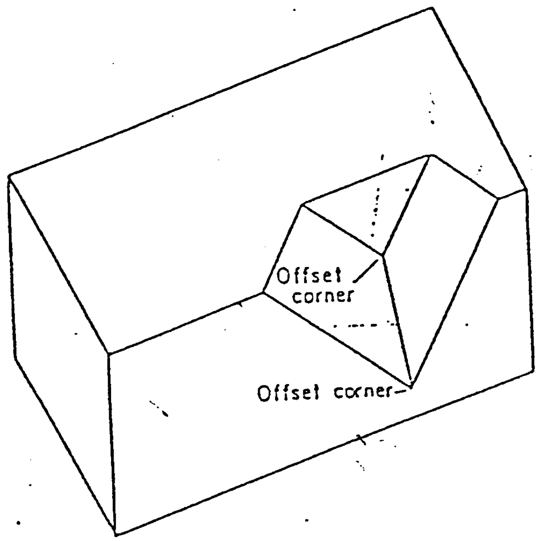



Figure 10. Diagram showing the geometry of a dyke wall with two offsets that intersect to form offset corners. (after Bussell, 1989, fig. 5)

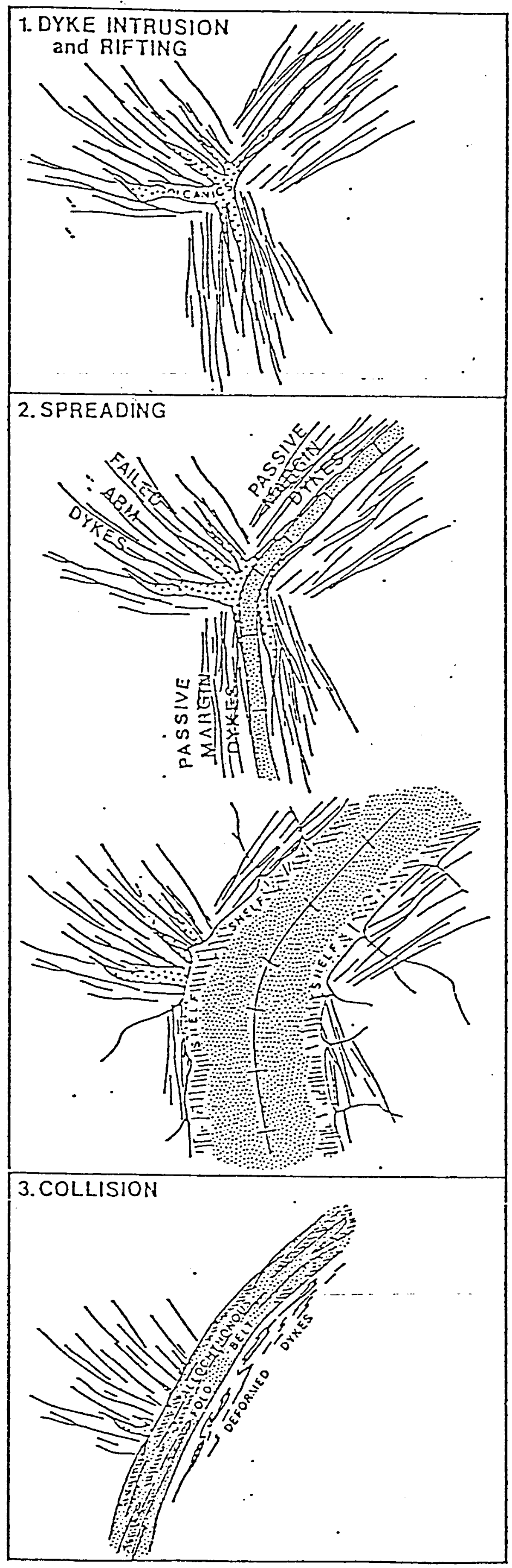



*Figure 11. Three-stage plate tectonic cycle in the development of mafic continental dyke swarms.*

(after Fahrig in Halls (ed), 1987, fig. 1) then the plane containing the dilation direction can be constructed through stereographic projection. The dilation plane will be represented by a great circle which contains the net dilation direction (Bussell, 1989). When two pairs of matching offsets from the same dike are present in the field, the actual dilation direction is defined by the intersection of both dilation planes (Fig.10). Dilation directions can only be determined if the dike walls have been preserved as intrusive contacts during emplacement (Bussell, 1989). Misleading dike offsets can originate from pinch and swell structures and boudins in the dike, faulting of the dike, and from angular blocks formed by stoping. Dike offsets formed by the linkage of en echelon structures can also create a misleading pair of offsets when bridging material is subjected to breakage and removal.

### Tectonic Settings of Dike Swarms

Through the use of dikes as regional structural markers, interpretations can be made regarding the tectonic setting of dike swarm development. Dike formation occurs in a regional extension direction most commonly associated with extensional tectonic settings such as rifts. Fahrig (1987) described three stages comprising a complete tectonic cycle of continental dike swarm development: 1) dike intrusion during continental rifting, 2) onset of ocean-floor spreading, and 3) closure of the ocean basin and continental collision (Fig. 11). Tensional forces acting on continental lithosphere will cause it to thin, creating a three-armed pattern of rifting, volcanism, and dike intrusion known as a triple junction. At the onset of subsequent ocean-floor spreading, two of three rift arms will constitute the zone of spreading containing earlier formed dikes on either side of a passive margin. If uplift occurs along the passive margin, the dikes may be subjected to removal by erosion. The third, failed arm, or aulacogen, becomes inactive and volcanism ceases. The closure of an ocean basin and ensuing collision typically deforms the passive margin dikes. However, remanent aulacogen dikes of the ancient rift system remain intact and extend deep into the continental interior.

The dike swarms of the latest Paleozoic-Mesozoic Karoo rift system in southern Africa represents the end of Fahrig's stage 1 rifting/dike intrusion and spreading of stage 2. The dikes parallel the arms of the Lower Zambesi - Lower Limpopo triple junction in which the north-south trending dikes represent the passive margin dikes of Fahrig's cycle (Fig. 12). The east-west trending dikes reflect a remanent aulacogen which extends deep into the continental interior.

The MacKenzie Dike Swarm of the northern Canadian Shield, is the largest in the world and encloses an area of 2.7 x $10^6$ $km^2$. They are 1.2 Ga old and represent an aulacogen of a rift triple junction system associated with the spreading of the Poseidon Ocean (Jackson & Iannili, 1981). The dikes form a gigantic fan southward, and are truncated to the north along the Arctic coastline (Fig. 13). Ancient rift-controlled basins containing volcanic rocks and overlying sedimentary sequences flank the Arctic focal point. Similar in age to the MacKenzie Dike Swarm are the Sudbury Dikes of the Great Lakes region. They share the same trend as the MacKenzie swarms and might hypothetically represent extensions of the MacKenzie. The Sudbury Dike Swarms concentrated east of Lake Superior, also mark a remanent aulacogen of an ancient spreading center (Sudbury Ocean) (Fahrig, 1987).

Evidence of a large-scale rifting event is represented by the Mesozoic dike swarms of eastern North America. The dikes record the rifting and opening of the North Atlantic Ocean. McHone et al (1987) recognized three distinct igneous provinces of eastern North America. The Eastern North American Dolerite Province (ENA), the Notre Dame Bay Igneous Province (NDB), and the New England-Quebec Igneous Province (NEQ) (Fig. 14). The three provinces differ in dike trend and distribution, age, and petrology. The ENA province is the largest and extends throughout the entire eastern Appalachian region from Alabama to southern New England. Dike trend and distribution changes reflect differential stress states along the ancient rift system. From the southern Appalachians to the Carolinas, dikes trend northwest; from the Carolinas to Pennsylvania, trends overlap and change to a north-south orientation; and from New Jersey into New England and the Atlantic Province of Canada, dike trends are northeast (Fig. 14) (McHone et al, 1987). Dikes of northern Newfoundland in the NDB province display gabbroic and

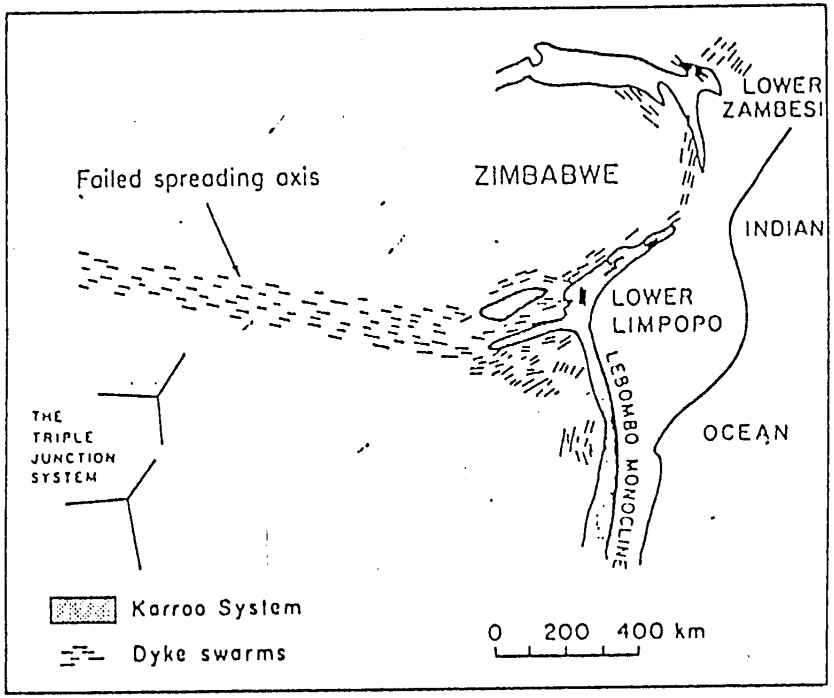
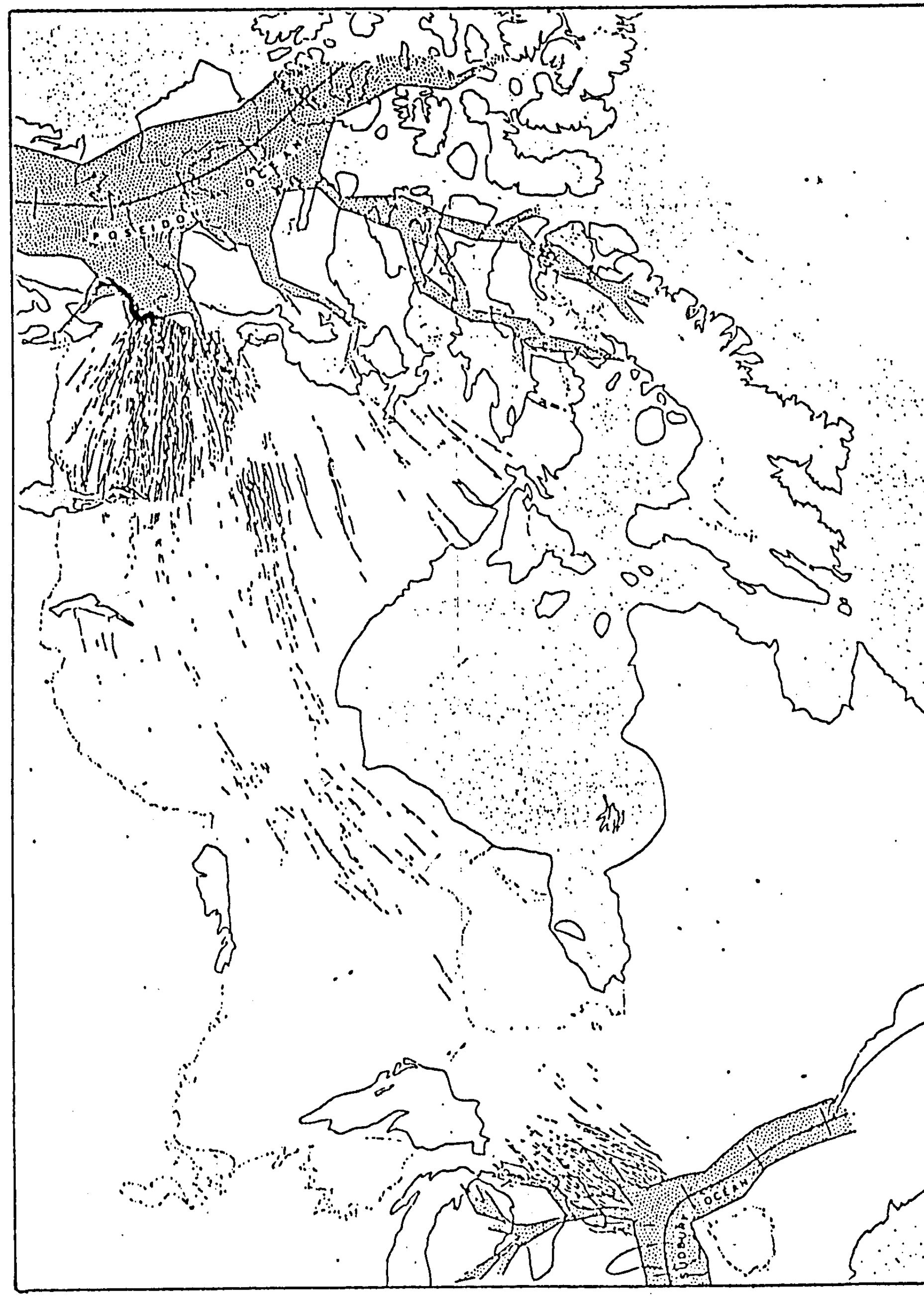



Figure 12. Basic dyke swarms of Karroo (Jurassic) age emplaced parallel to triple junction boundaries near the downwarped rifted continental margin of southeast Africa (compiled from Vail, 1970; Burke and Dewey, 1973a; Reeves, 1978)

(after Windley, 1984, fig. 16.7)



'gure 13. *The relationship between ocean development and intrusion of Mackenzie and Sudbury dyke* ›*arms. The Sudbury dykes are those in the Great Lakes region, and hypothetical extensions of this* ›*arm (in halftone) are shown because Sudbury dykes are known to extend into the Grenville Province* '*here they are metamorphosed.*

(after Fahrig in Halls (ed), 1987, fig. 2)

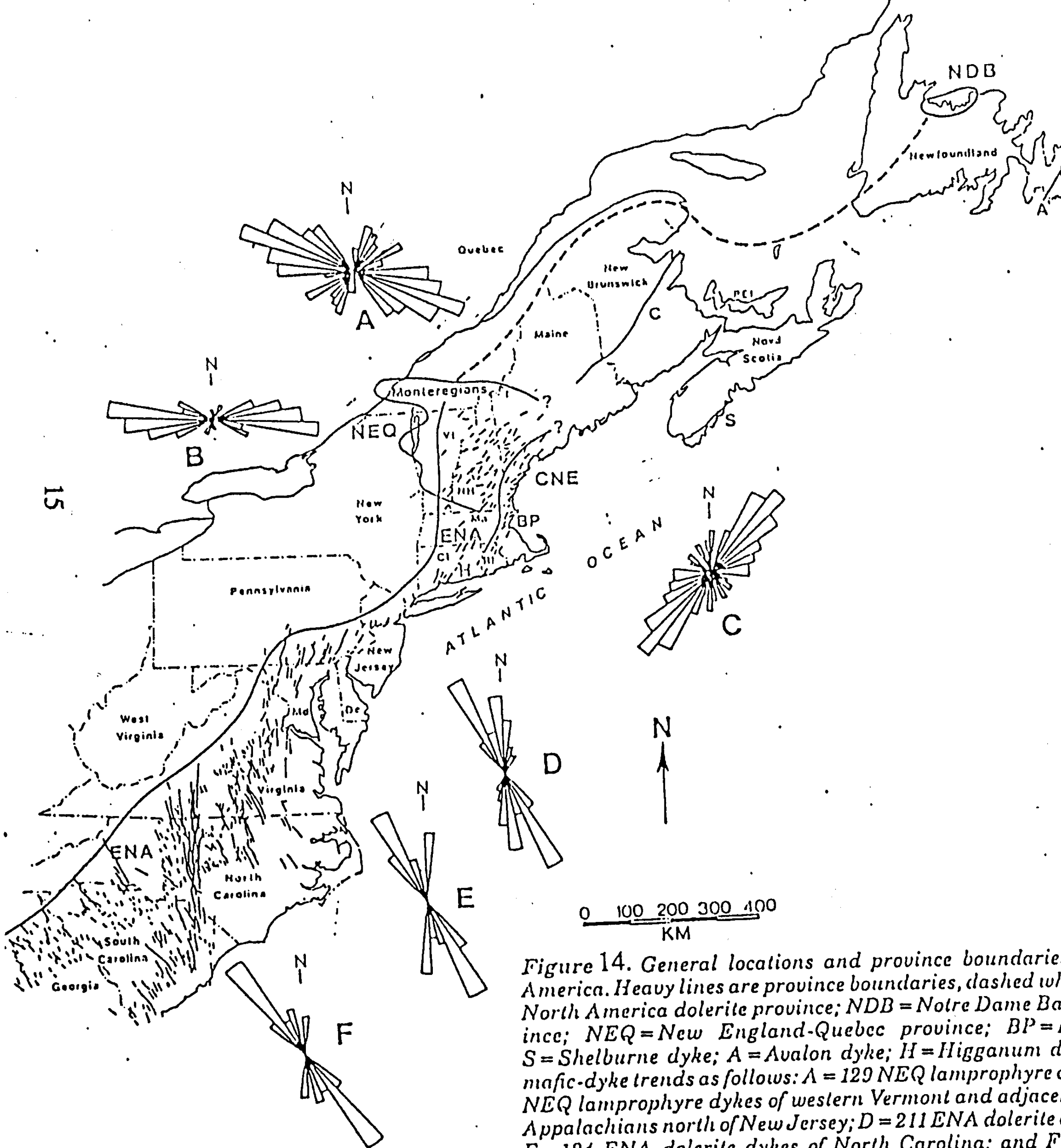



Figure 14. General locations and province boundaries of Mesozoic dyke swarms in eastern North America. Heavy lines are province boundaries, dashed where conjectural. Abbreviations: ENA = Eastern North America dolerite province; NDB = Notre Dame Bay province; CNE = Coastal New England province; NEQ = New England-Quebec province; BP = Boston Platform area; C = Caraquet dyke; S = Shelburne dyke; A = Avalon dyke; H = Higganum dyke. Rose diagrams A-F are constructed from mafic-dyke trends as follows: A = 129 NEQ lamprophyre dykes of the Monteregian area of Quebec; B = 155 NEQ lamprophyre dykes of western Vermont and adjacent New York; C = 239 ENA dolerite dykes of the Appalachians north of New Jersey; D = 211 ENA dolerite dykes of Pennsylvania, Maryland, and Virginia; E = 184 ENA dolerite dykes of North Carolina; and F = 179 ENA dolerite dykes of South Carolina, Georgia, and Alabama. (after McHone et al. in Halls (ed), 1987, fig. 1)

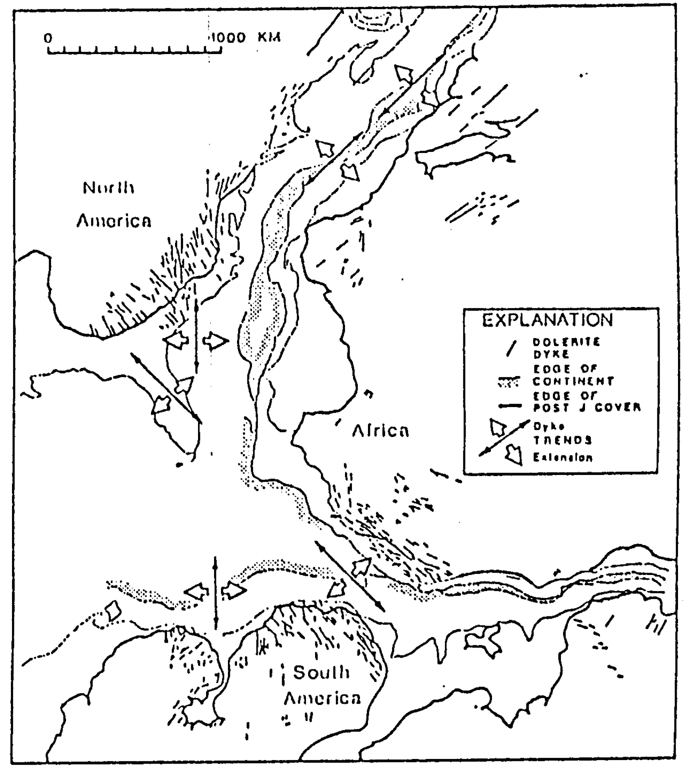



Figure 15. General locations and trends of Early Jurassic dolerite dykes around the initial central Atlantic Ocean basin, modified from May (1971), with additions from Ragland et al. (1983), McHone (1984), Ross (1985), Papezik and Greenough (1985), H. Bertrand (personal communication, 1986), and Gibbs (this volume).

(after McHone et al. in Halls (ed), 1987, fig. 2) lamprophyric petrography. They trend generally northeast and are dated from early Cretaceous times. The NEQ province dikes also date from the early Cretaceous (96 - 136 Ma) and are generally bimodal (syenite-gabbro) and alkalic. Dike trends are near N65W in Quebec, nearly east-west in the Lake Champlain Valley between Vermont and New York, and between N45E and N60E in southern and eastern Vermont and elsewhere in New England (McHone et al, 1987). Dikes of these latter provinces (NDB & NEQ) are generally alkaline in nature whereas the Early Jurassic ENA dikes are quartz and olivine tholeiitic dolerites. The three different dike trends of the ENA province and the trends of Early Jurassic dikes in Africa and South America closely parallel three rifting directions that opened the Atlantic Ocean basin (Fig. 15).

Dike swarms also record paleostress directions in foreland regions of continental collisional belts. Analysis of intraplate deformation shows the close relationship between compression and distension in a regionally compressive setting (Feraud et al, 1987). Feraud, Giannerini and Campredon (1987) described areas in the European and northwest Arabian plate margins where Cenozoic dike swarms have indicated paleostress fields adjacent to collisional belt systems. In southern France, a compressional stress field resulted from the formation of the occidental Alpine arc and NNW convergent motions of converging European and African plates. Dike formation in the foreland of the Alpine arc (west) are approximately normal to the collision zone and their trends parallel the direction of the maximum horizontal paleostress field that existed at the time of intrusion. Cenozoic dike swarms in northwest Arabia resulted from volcanic-injected tensional gashes produced during the Arabian/Indo-European plate collision. Extension is generated in response to lateral escape of lithosphere away from the northward advancing Arabian plate. If tensional stresses exceed horizontal compressive stresses, grabens may form in foreland regions of collisional systems. Figure 16 compares synchronous tectonic events and the development of dikes in response to compressive stresses. The Levantine rift zone in northwest Arabia is marked by tension-induced grabens where northeast-southwest tensile stresses opened the pre-existing Levantine Fault. Similar tectonic settings of this nature also occur in Europe where development of

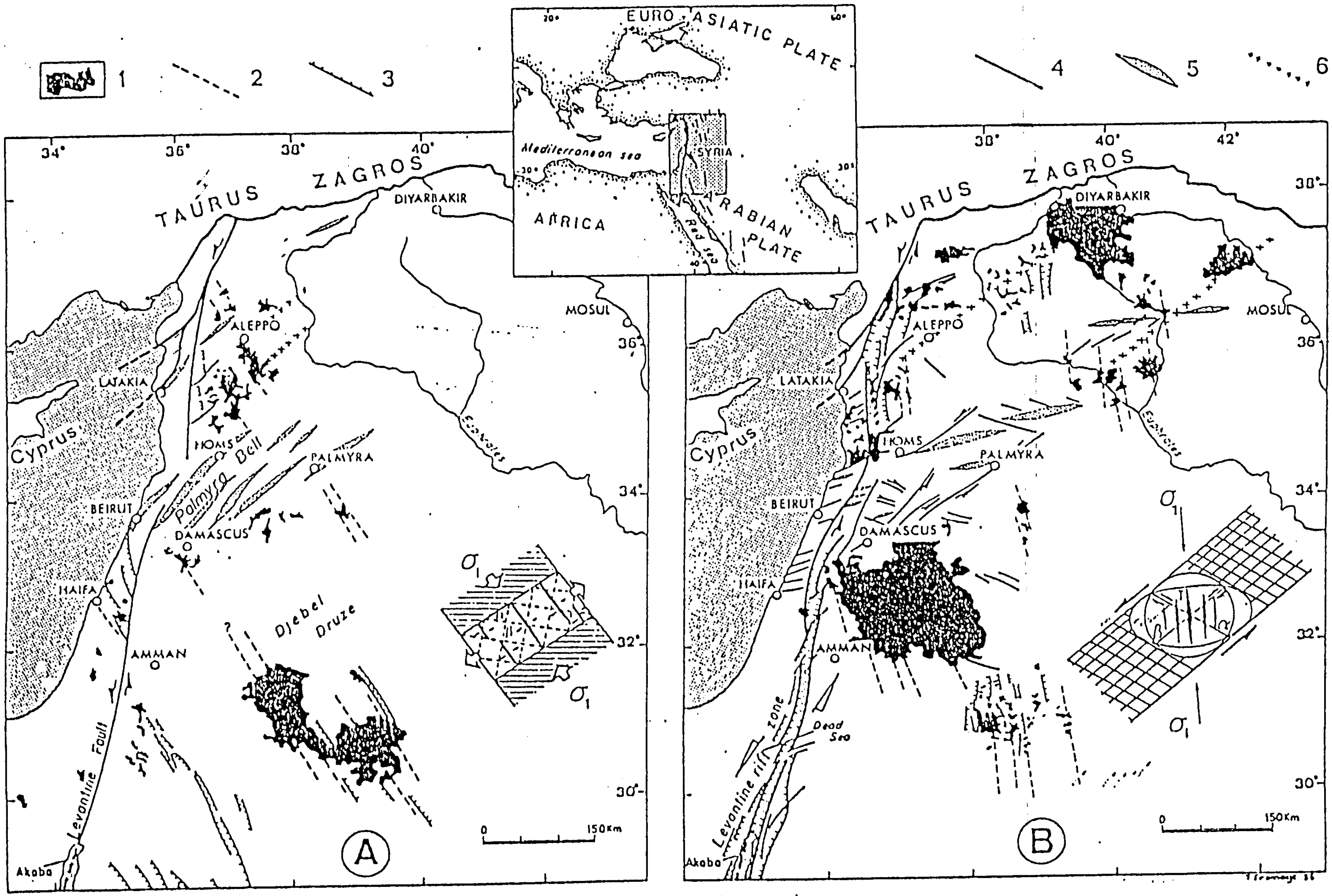



Figure 16. *Synchronous tectonic events and magmatic products (dykes and cone alignments) in the NW portion of the Arabian plate. Legend: 1, basaltic formations; 2, dyke and volcanic-cone alignment directions; 3, normal faults; 4, strike-slip faults; 5, folds; 6, lines of potential strike-slip motion. A: Miocene period (20 to 5 Ma); B: Plio-Quaternary period (5 to 0 Ma). The orientation of the stress field and mechanism of dyke formation are schematically given for different areas. α = dextral, β = sinistral strike-slip.*

(after Feraud et al. in Halls (ed), 1987, fig. 2) the Rhine Graben initiated from compressional deformation of the Alps during Eocene-Oligocene time. Rifting continued in the foreland region during most of the Tertiary as Alpine compressional deformation continued.

## DIKE SWARMS OF THE TRANSANTARCTIC MOUNTAINS

### Geographic Distribution

The occurrences of mafic dike swarms in southern Victoria Land have been noted during previous geological investigations and schematic mapping of the region. These diagrammatical illustrated dike localities from earlier maps have been compiled along with recently derived systematic data from Granite Harbour (Wilson, unpublished data, 1989) on a base map of the McMurdo Sound sector of the Transantarctic Mountains (Fig. 17 and Plate 1) (Plate 1 is a portion taken from the Ross Island and Vicinity topographic map, scale 1:250,000, U.S.G.S., 1986). The area in which dike swarms have been mapped is approximately 150 km along strike from Mackey Glacier in the north to Koettlitz Glacier in the south and 70 km across strike inland from McMurdo Sound. Wilson (personal observations, 1989) recorded dike trends at five localities in the Granite Harbour region; First View Point, Avalanche Bay, Discovery Bluffs/Cape Geology, Minnehaha Ice Falls, and Mt. Suess. Previously recorded observations of dike trends were also documented at Granite Harbour by Gunn and Warren (1962), which they defined as the type area for "all the plutonic and hypabyssal intrusives" of the Ross Orogeny. Other investigations which noted dike occurrences included areas of the Victoria Valley (Allen and Gibson, 1962), the Wright Valley along the Olympus Range by McKelvey and Webb (1962), the Taylor Valley between the Asgard Range and Kukri Hills by Haskell and others (1965), and the Blue Glacier and Koettlitz Glacier region by Blank and others (1963).

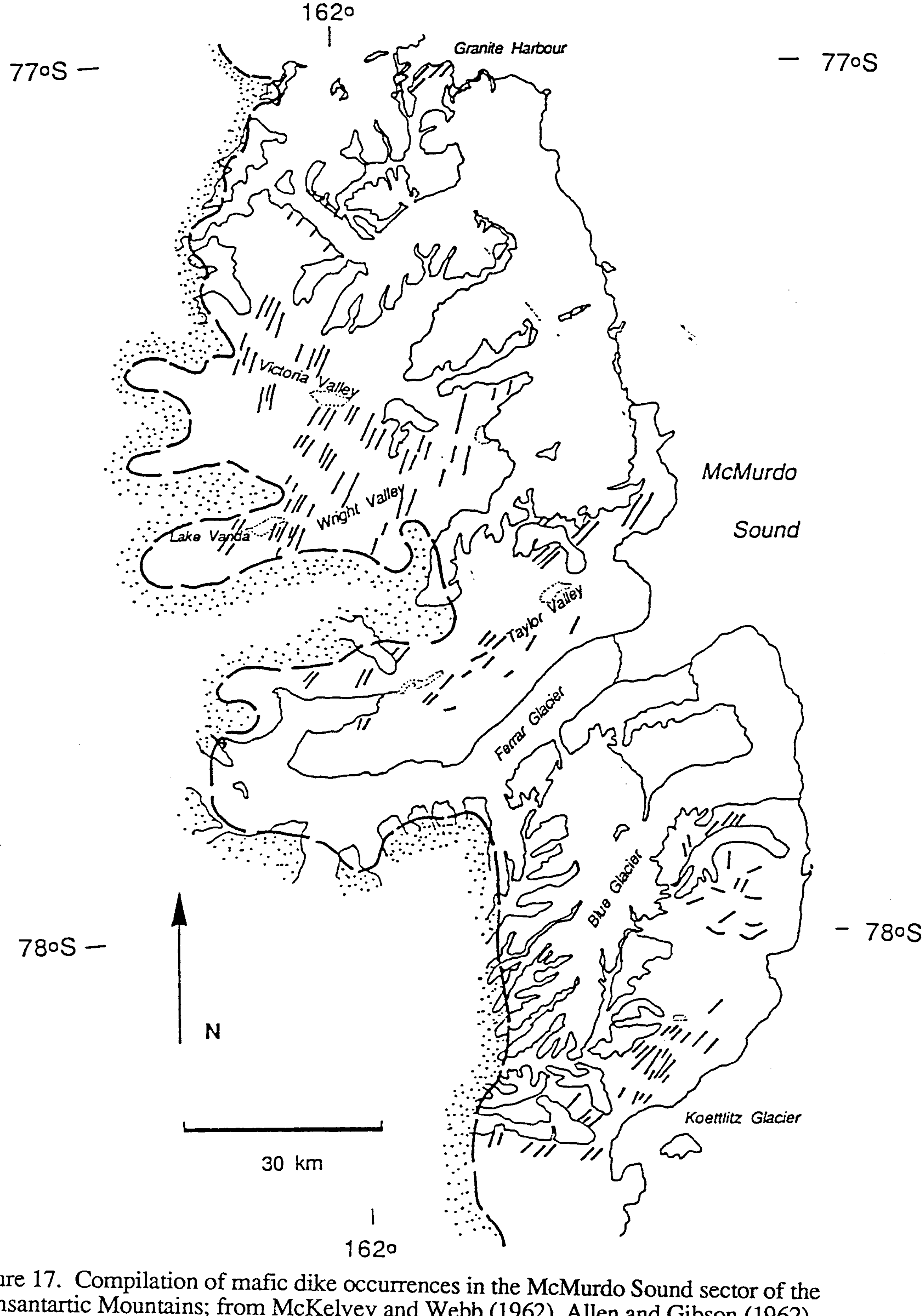



Figure 17. Compilation of mafic dike occurrences in the McMurdo Sound sector of the Transantartic Mountains; from McKelvey and Webb (1962), Allen and Gibson (1962), Gunn and Warren (1962), Blank et al.(1963), and Wilson from Granite Harbour (unpublished, 1989). Heavy dashed line = 'Kukri peneplain' unconformity at the base of the Beacon Supergroup (shown by stippled pattern); dikes shown by short heavy lines. Orientation data for Granite Harbour area shown in Figure 19.

**Petrology of the Dikes**

Dikes of pre-Beacon age are distinguished from each other by differing compositions and appreciable metamorphism (Blank et al., 1963). They are described as intermediate to basic diorites, lamprophyres, and porphyries and acidic quartzo-feldspathic aplites, pegmatites and microgranites.

Haskell et al. (1965) described augite-biotite lamprophyres and hornblende lamprophyres as the most abundant dikes in the area of Nussbaum Riegel and Mt. Coleman in the Kukri Hills and Lower Taylor Valley. Augite -biotite lamprophyres were noted as being grey to black, strongly porphyritic, and moderately metamorphosed and slightly deformed. Hornblende lamprophyres, the youngest of the mafic dikes, were described as dark -grey to black, aphanitic, and dominated by phenocrysts of brown hornblende. Other basic to intermediate dike rocks noted were relatively rare, strongly porphyritic, mesocratic porphyries, and tremolite/actinolite diorite dikes that were medium-grained with a distinctive greenish hue. Microgranite dikes were observed as occurring in several types including a porphyritic type containing light-colored phenocrysts of mainly orthoclase and quartz set in a dark grey or brown matrix. Additional petrographic descriptions of dikes from the Taylor Valley were made by Manzoni and Nanni (1977), who described dike samples as homogeneous with a microporphyritic seriate texture consisting of subequal amounts of zoned euhedral plagioclase and elongate amphibole phenocrysts.

In the Koettlitz-Blue Glacier region Blank et al. (1963) also noted occurrences of biotite lamprophyres (subschistose to schistose, strongly deformed and containing andesine, augite and hornblende), abundant hornblende lamprophyres, porphyries, acidic aplites (less common) and coarse to fine grained pegmatites. McKelvey and Webb (1962) recognized the "Vanda Lamprophyre and Porphyry" dikes at their type locality east of Lake Vanda in the Wright Valley. Two types of lamprophyres and acid porphryries (porphryries divided on feldspar and quartz content) were described. Also described by McKelvey and Webb were the "Loke Microdiorite" dike swarms (biotite and hornblende dominated) that intrude the Olympus Granite-gneiss at Mt. Loke. Allen and Gibson (1962) used the "Vanda Lamprophyre and Porphyry " nomenclature proposed by McKelvey and Webb (1962) to describe the extensive dike swarms on Sponsors Peak, the Insel Range, and west of Clark Glacier in the Victoria Valley region. Vanda Lamprophyres are dark aphanitic dikes composed of zoned plagioclase, hornblende, chlorite, quartz, and iron oxide. Vanda Porphyry dikes contain conspicuous orthoclase and some quartz phenocrysts in a fine-grained groundmass. Within their "Granite Harbour Intrusive Complex," Gunn and Warren (1962) reported occurrences of the following dikes in order of increasing age: basaltic and doleritic dikes related to the Ferrar Dolerites, lamprophyre dikes composed mainly of plagioclase in a porphyritic texture, microgranite dikes found near plutons of the Irizar Granite, and medium to fine-grained quartzo-feldspathic dikes.

Evidence of lower crustal and possible upper mantle granulite inclusions have been documented from Cambro-Ordovician lamprophyre dikes from the Roaring Valley and Pipecleaner Glacier regions (Berg, 1988). Two feldspar thermometry analyses yielded equilibrium temperatures of $900^{0}$C and pressures of 13.3 kilobars (with +1.6-kilobar correction) reflecting a crustal depth of 45 km. The "extremely pristine" condition of one of the samples would indicate that lower crustal magma must not have assimilated in a batholith but rather propagated quite rapidly to the surface. The origination of upper mantle or lower crustal-derived inclusions seems statistically unlikely (Berg, 1988) and would therefore put crustal thicknesses greater than 45 km., indicative of deformation and crustal thickening associated with the Cambro-Ordovician Ross Orogeny.

## Ages of the Dikes

Ages of dike swarm occurrences attained by K-Ar and Rb-Sr radiometric dating techniques of the 1960's provided poorly constrained cooling ages for the dikes of the Transantarctic Mountains. Angino, Turner, and Zeller (1962) using K-Ar dating of a biotite lamprophyre in the

Taylor Valley established the age of the dike at 458 m.y. ± 20 m.y. and a biotite age from a monzonitic gneiss at 425 ± 20 m.y. from the Nussbaum Riegel region of the Taylor Valley. Deutsch and Webb (1964) through Sr-Rb dating of a porphyry dike in Olympus granite-gneiss, dated biotite, feldspar, and whole rock samples at 477 m.y., 942 m.y., and 1000 m.y. respectively. Jones and Faure (1967) reported that an age of 1000 m.y. was inconsistent with field relations. They sampled a porphyry which intruded the Åsgard Fm that contained a higher concentration of K-feldspar and dated it using Sr-Rb techniques to obtain an age of 470 m.y.. Subsequent investigations by Faure and Jones (1974) discovered low Rb-Sr ratios in the Vanda Lamprophyres and dated both the Vida Granites and Vanda Porphyries of the Victoria Granites instead. They obtained an age through Sr-Rb dating of 481 ± 44 m.y. (the large uncertainty is due to the combined isochron). Recalculations of old dates obtained by Deutsch and Webb (1964) and Jones and Faure (1967) were provided by Skinner (1983) using new decay constants and yielded dates of 465 ± 15 m.y. for a hornblende-biotite porphyry and 460 ± 7 for a whole rock-feldspar porphyry isochron at m.y. respectively.

Graham and Palmer (1987) investigated two Granite Harbour granitoids (Avalanche Bay Quartz-monzodiorite and Lion Island Granite) located 18 km. apart, which revealed similar Rb-Sr mineral and whole rock dates of 473 ± 8 m.y.. Based on the Gunn and Warren (1962) division of the "Granite Harbour Intrusive Complex" into pre-, syn-, and post-tectonic suites, the Avalanche Bay Quartz-monzodiorite and Lion Island Granite are considered post-tectonic and equivalent in age to the Vida Granite (Table 1 and Table 2). Wilson (1989 personal observations) noted the Avalanche Bay and Lion Island granitoids were cut by the mafic dikes, which therefore establishes a lower age limit of these mafic dikes at 473 ± 8 m.y.

## Orientations and Relative Ages of Mafic Dike Swarms

A general northeast trend for the mafic dikes of the McMurdo Sound sector is apparent from Granite Harbour to the Koettlitz Glacier region (Fig. 17, Plate 1). Evidence for different

Table 1: Analytical data for Granite Harbour Granitoids

| Catalogue Number | Material | Rb | Sr | $^{87}Rb/^{86}Sr$ | $^{87}Sr/^{86}Sr$ * | Age | Intercept |
|---|---|---|---|---|---|---|---|
| **Avalanche Bay Quartz-monzodiorite** | | | | | | | |
| 30844 | whole-rock | 121.2 | 696.4 | 0.5039 | 0.71217 ) | | |
| 30844 | feldspar | 74.2 | 829.4 | 0.2592 | 0.71051 ) | 471 ± 5 | 0.70877 ± 3 |
| 30844 | hornblende | 82.8 | 152.6 | 1.5726 | 0.71923 ) | | |
| 30844 | biotite | 358.8 | 40.3 | 26.2224 | 0.88539 ) | | |
| 30846 | whole-rock | 128.1 | 720.5 | 0.5150 | 0.71236 ) | | |
| 30846 | feldspar | 83.7 | 875.1 | 0.2771 | 0.71079 ) | 476 ± 3 | 0.70889 ± 2 |
| 30846 | hornblende | 120.6 | 146.0 | 2.3953 | 0.72514 ) | | |
| 30846 | biotite | 344.0 | 43.0 | 23.5241 | 0.86856 ) | | |
| **Lion Island Granite** | | | | | | | |
| 30802 | whole rock | 199.8 | 223.9 | 2.5882 | 0.72638 ) | | |
| 30802 | feldspar | 141.3 | 219.0 | 1.8703 | 0.72130 ) | 469 ± 12 | 0.70889 ± 24 |
| 30802 | biotite | 685.5 | 53.4 | 38.0903 | 0.96290 ) | | |
| 30801 | whole rock | 211.4 | 126.2 | 4.8656 | 0.74204 ) | | |
| 30803 | whole rock | 204.9 | 207.2 | 2.8685 | 0.72780 ) | 473 ± 26 : | 0.70877 ± 66 |
| 30804 | whole rock | 152.4 | 71.1 | 6.2313 | 0.75044 ) | (473 ± 8 ** | 0.70883 ± 7) |

* NBS987 = 0.71010 ± 0.00005
Blanket errors used in York regression (1σ) : 1% on $^{87}Rb/^{86}Sr$; 0.007% on $^{87}Sr/^{86}Sr$

: includes 30802

** includes 30802, 30844, 30846

(after Graham and Palmer, 1987, Tables 1)

Table 2: Summary of previous Rb-Sr age determinations from South Victoria Land.

| | $^{87}Sr/^{86}Sr$ | Age (Ma) | Type | Locality |
|---|---|---|---|---|
| **"Syn-tectonic" granites** | | | | |
| Deutsch and Webb [1964] | 0.709* | 479 ± 15 | Biotite | Wright Valley |
| | 0.709* | 495 ± 15 | Biotite | Wright Valley |
| | 0.709* | 487 ± 15 | Biotite | Wright Valley |
| Faure and Jones [1974] | 0.7109 ± 0.0067 | 499 ± 43 | Whole rock: | Wright Valley |
| **"Post-tectonic" granites** | | | | |
| Deutsch and Webb [1964] | 0.709* | 472 ± 15 | Biotite | Victoria Valley |
| Faure and Jones [1974] | 0.7104 ± 0.0008 | 481 ± 44 | Whole rock' | Wright Valley |
| Stuckless and Erickson [1975] | 0.7098 ± 0.0008 | 475 ± 14 | Whole rock | Victoria Valley |

All ages recalculated using the decay constant = $1.42 \times 10^{-11} a^{-1}$ (Steiger and Jäger, 1977).

* assumed initial ratio for model recalculations
: includes Olympus Granite-gneiss
' includes Vanda porphyry

(after Graham and Palmer, 1987, Tables 2) generations of dikes and relative ages of dike sets with different orientations is attained from observing cross-cutting relationships in the field. Angino et al. (1962) differentiated four lamprophyric dike systems in the Lower Taylor Valley from Lake Bonney to McMurdo Sound near Nussbaum Riegel (Fig. 18). Based on cross-cutting relationships, they devised a tentative order of emplacement of these dikes with the initial injection of a north-northwest lamprophyric system followed by cutting of a east and east-northeast-striking dike series. A final north-northwest system was subsequently emplaced, cutting previously injected dike systems. Additional investigations by Gunn and Warren (1962) of dike occurrences in the McMurdo Sound region and Haskell et al. (1965) in the Middle and Lower Taylor Valley noted that lamprophyre and porphyry dikes generally trend east or northeast. Augite-biotite lamprophyres only cut the Wright Intrusives of the "Granite Harbour Intrusive Complex" and are considered to be the oldest of the subsequent cross-cutting microgranite, microdiorite, ultrabasic, porphyry, and hornblende lamprophyre dikes. In the Victoria Dry Valley and areas below Mt. Insel, Webb and McKelvey (1959) reported two uniform lamprophyre dike systems intersecting each other; one set consisted of fifty northeast-striking dikes cropping out over a distance of one mile intersected by six northwest-striking dikes. In the Koettlitz-Blue Glacier region, Blank et al. (1963) also noted the occurrence of northeast-striking older biotite and younger hornblende lamprophyres and porphyry dikes based on cross-cutting relationships.

Systematic measurements of lamprophyre and porphyry dike trends in the Granite Harbour-MacKay Glacier region were taken by Wilson (unpublished, 1989) during field work in the area. Orientations from five localities (First View Point, Avalanche Bay, Discovery Bluffs/Cape Geology, Minnehaha Ice Falls, and Mt. Suess) are represented on stereoplots in Fig. 19. Average dike orientations from the five localities are as follows: Avalanche Bay N32E, 76E; First View Point N40E, 84E; Discovery Bluffs/Cape Geology N216E, 81W; Minnehaha Ice Falls N218E, 82W; Mt. Suess N27E, 77E. At Avalanche Bay, 10 orientations were taken in which 2 of them deviated from a well-defined northeast trend the other 8 depicted and one of those two had a

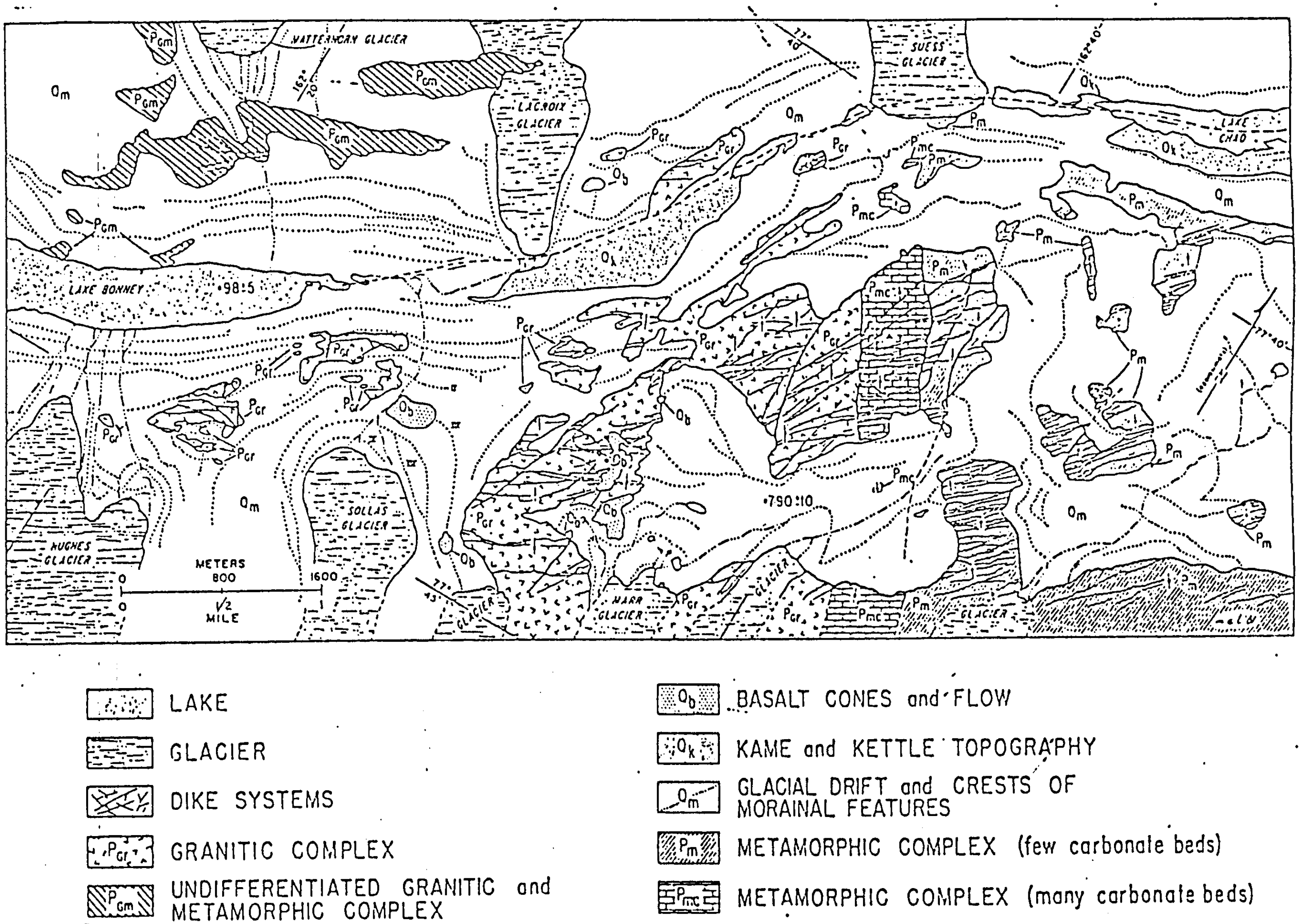



Figure 18. Map of Lower Taylor Valley from Lake Bonney to Lake Chad. Location of Mt. Nussbaum indicated by a solid triangle in right center. Elevations (as: 38 ± 5 m) in meters. Heavy solid or dashed lines indicate faults. Light lines of alternating dashes and dots are intermittent streams. All geographic names approved by New Zealand Geographic Board, and names of major glaciers have received tentative approval by U.S. Office of Geography (written communication, Oct. 27, 1961). Note added in proof: The latest elevation data for Lake Bonney give 38 ± 5 m rather than 98 ± 5 m. (after Angino et al., 1962, fig. 3)

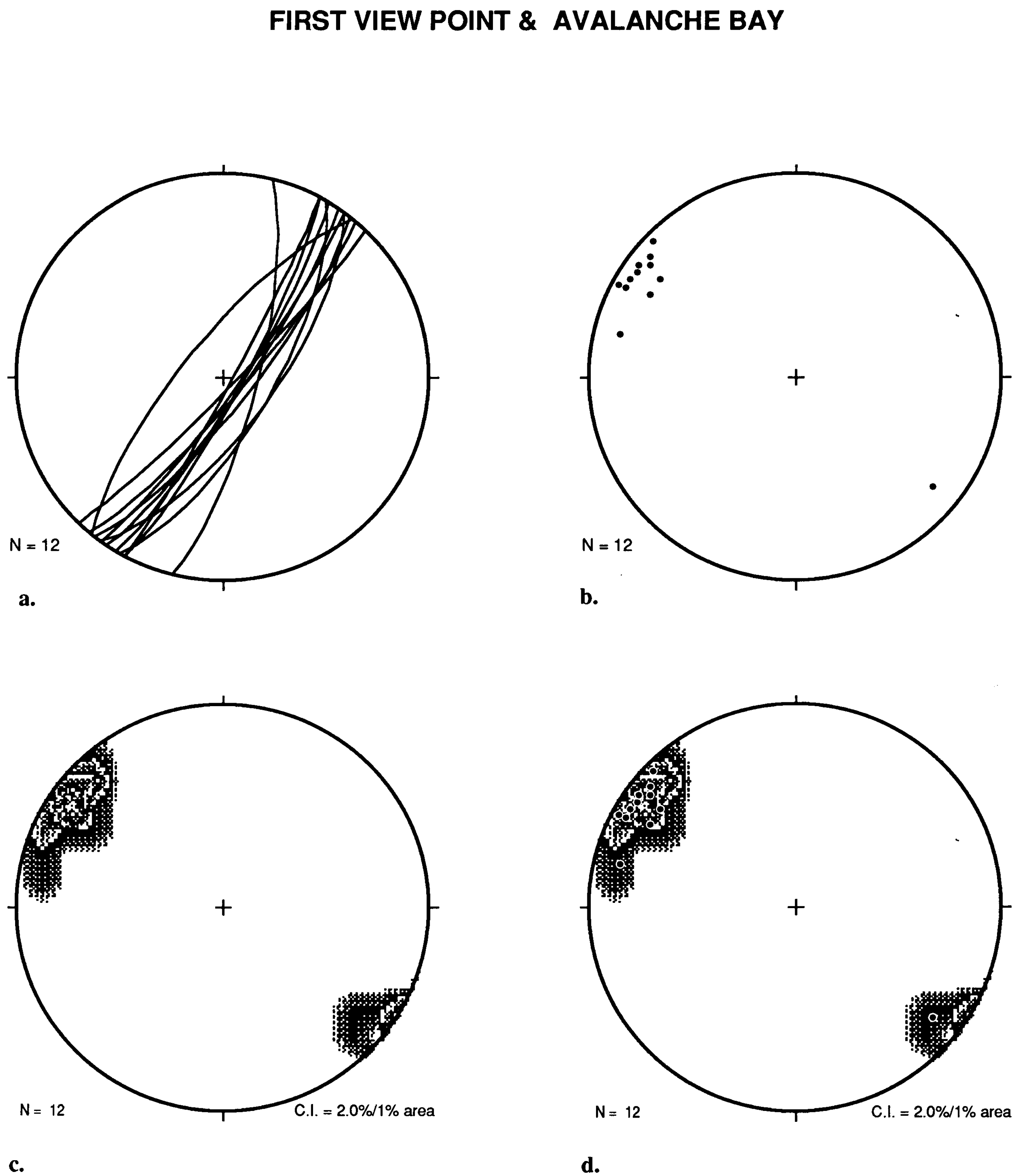



FIGURE 19. Stereoplots of dike orientations from First View Point & Avalanche Bay localities of Granite Harbour region. a) Great circle plot showing strike and dip of dike planes, b) scatter plot of poles to dike planes, c) contoured of poles to dike planes, and d) contour plot with poles.

# DISCOVERY BLUFFS/CAPE GEOLOGY

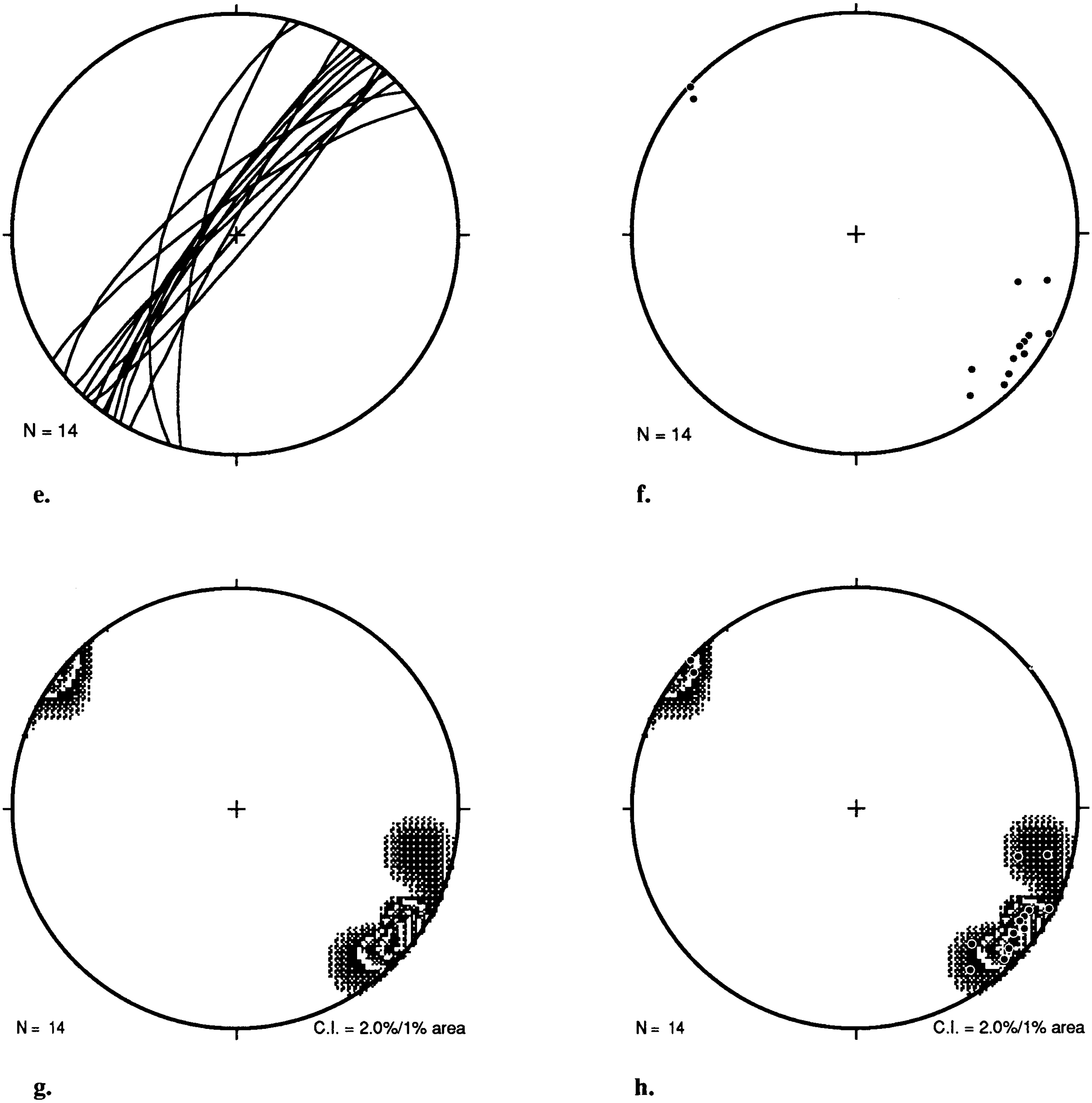



FIGURE 19. Stereoplots of dike orientations from Discovery Bluffs/Cape Geology localities of Granite Harbour region. e) Great circle plot showing strike and dip of dike planes, f) scatter plot of poles to dike planes, g) contoured of poles to dike planes, and h) contour plot with poles.

## FIRST VIEW POINT , AVALANCHE BAY, &
## DISCOVERY BLUFFS/CAPE GEOLOGY

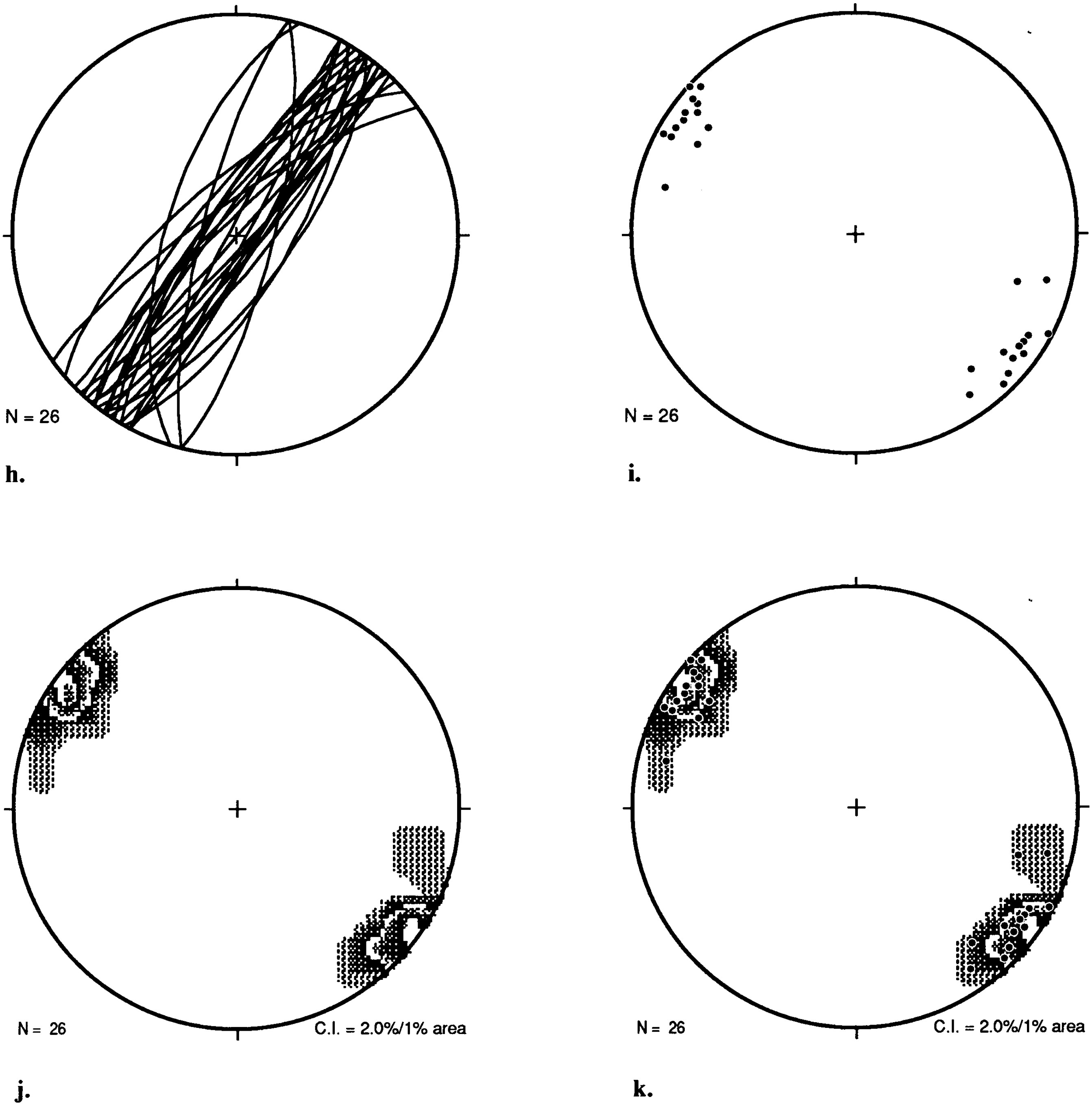



FIGURE 19. Stereoplots of dike orientations from First View Point, Avalanche Bay, and Discovery Bluffs/Cape Geology localities of Granite Harbour region. h) Great circle plot showing strike and dip of dike planes, i) scatter plot of poles to dike planes, j) contoured of poles to dike planes, and k) contour plot with poles.

# MINNEHAHA ICE FALLS

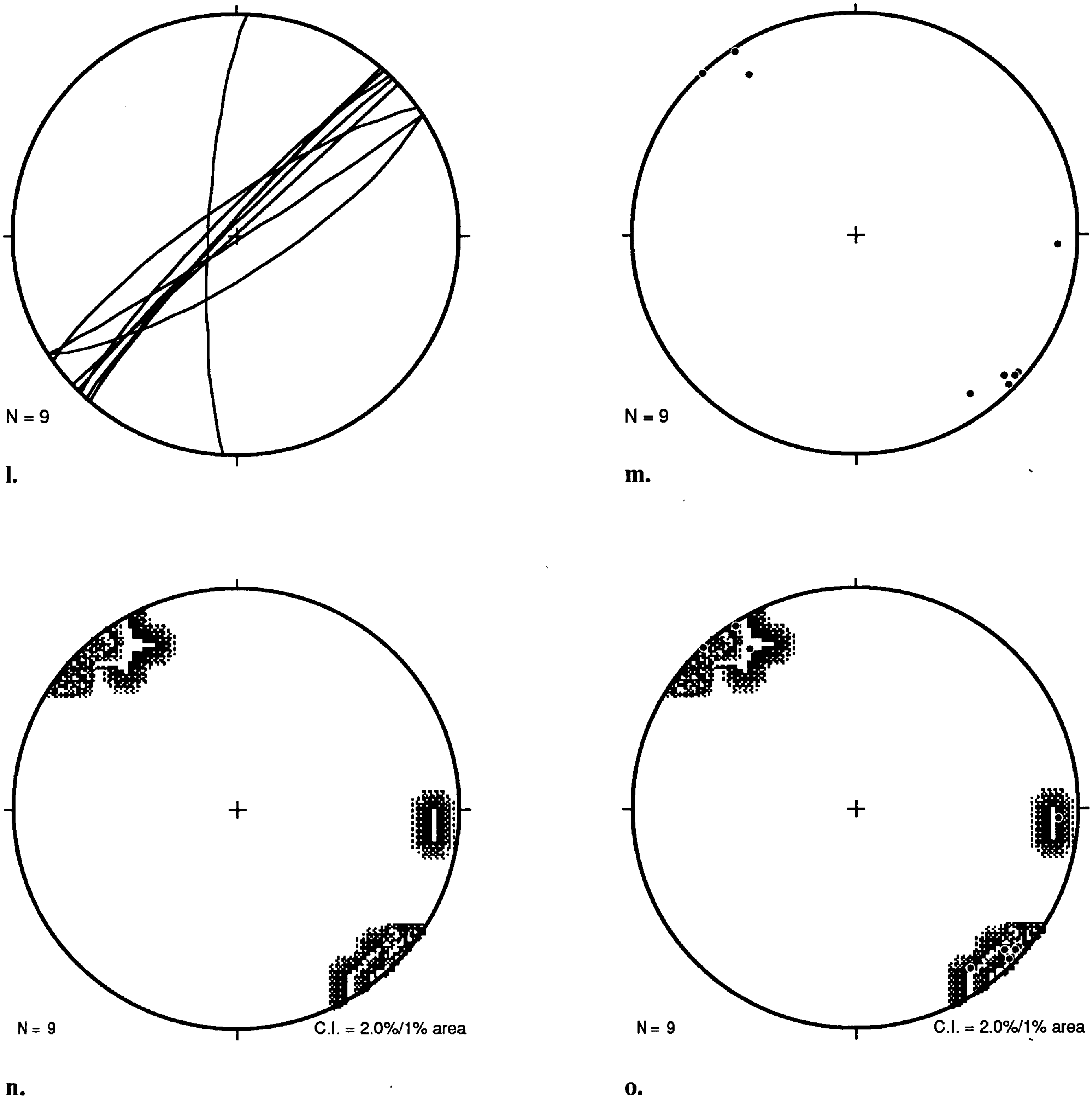



FIGURE 19. Stereoplots of dike orientations from Minnehaha Ice Falls locality of Granite Harbour region. l) Great circle plot showing strike and dip of dike planes, m) scatter plot of poles to dike planes, n) contoured of poles to dike planes, and o) contour plot with poles.

## FIRST VIEW POINT, AVALANCHE BAY, DISCOVERY BLUFFS/CAPE GEOLOGY, & MINNEHAHA ICE FALLS

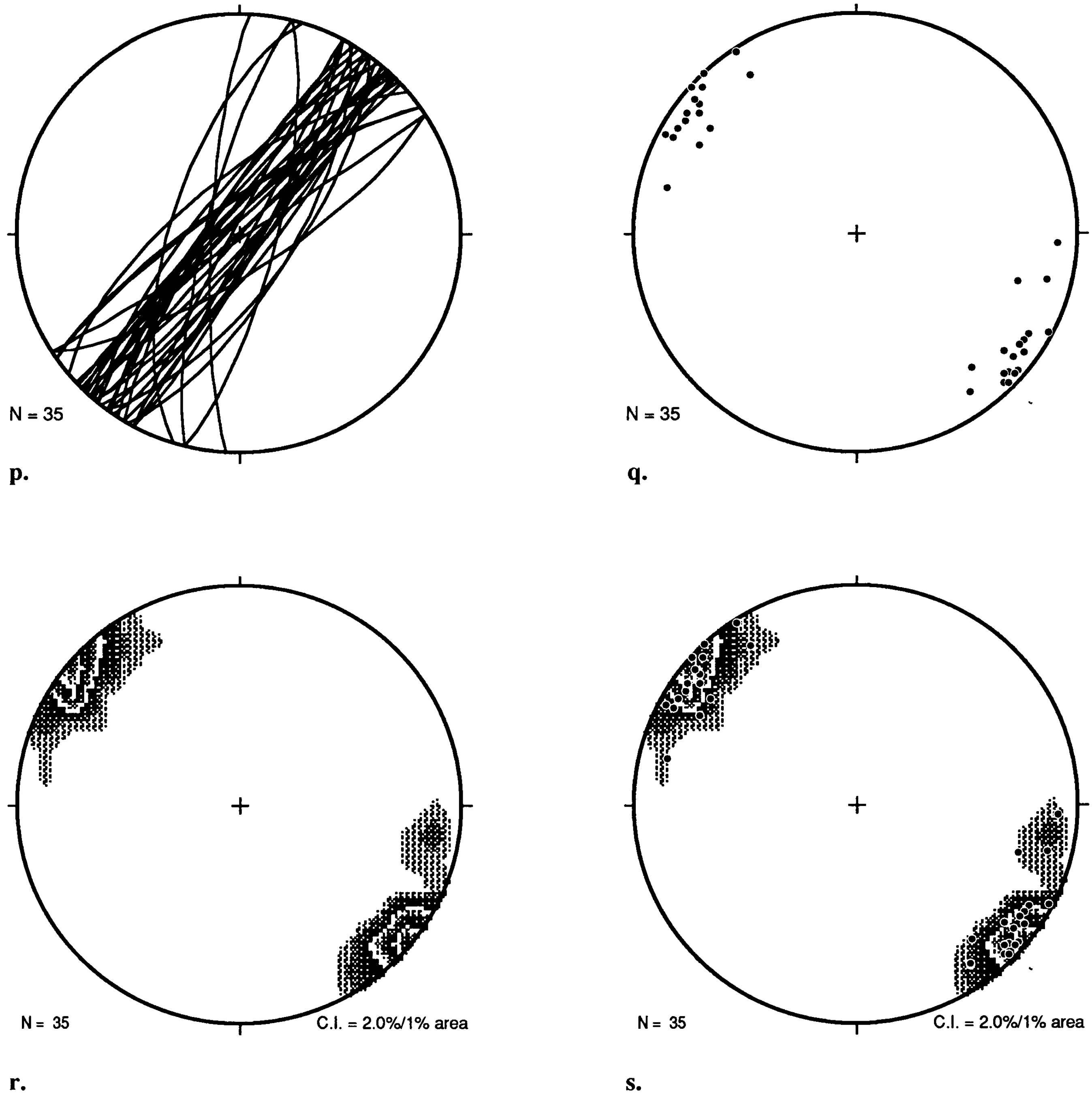



FIGURE 19. Stereoplots of dike orientations from First View Point, Avalanche Bay, Discovery Bluffs/Cape Geology, and Minnehaha Ice Falls localities of Granite Harbour region. p) Great circle plot showing strike and dip of dike planes, q) scatter plot of poles to dike planes, r) contoured of poles to dike planes, and s) contour plot with poles.

## MT. SUESS

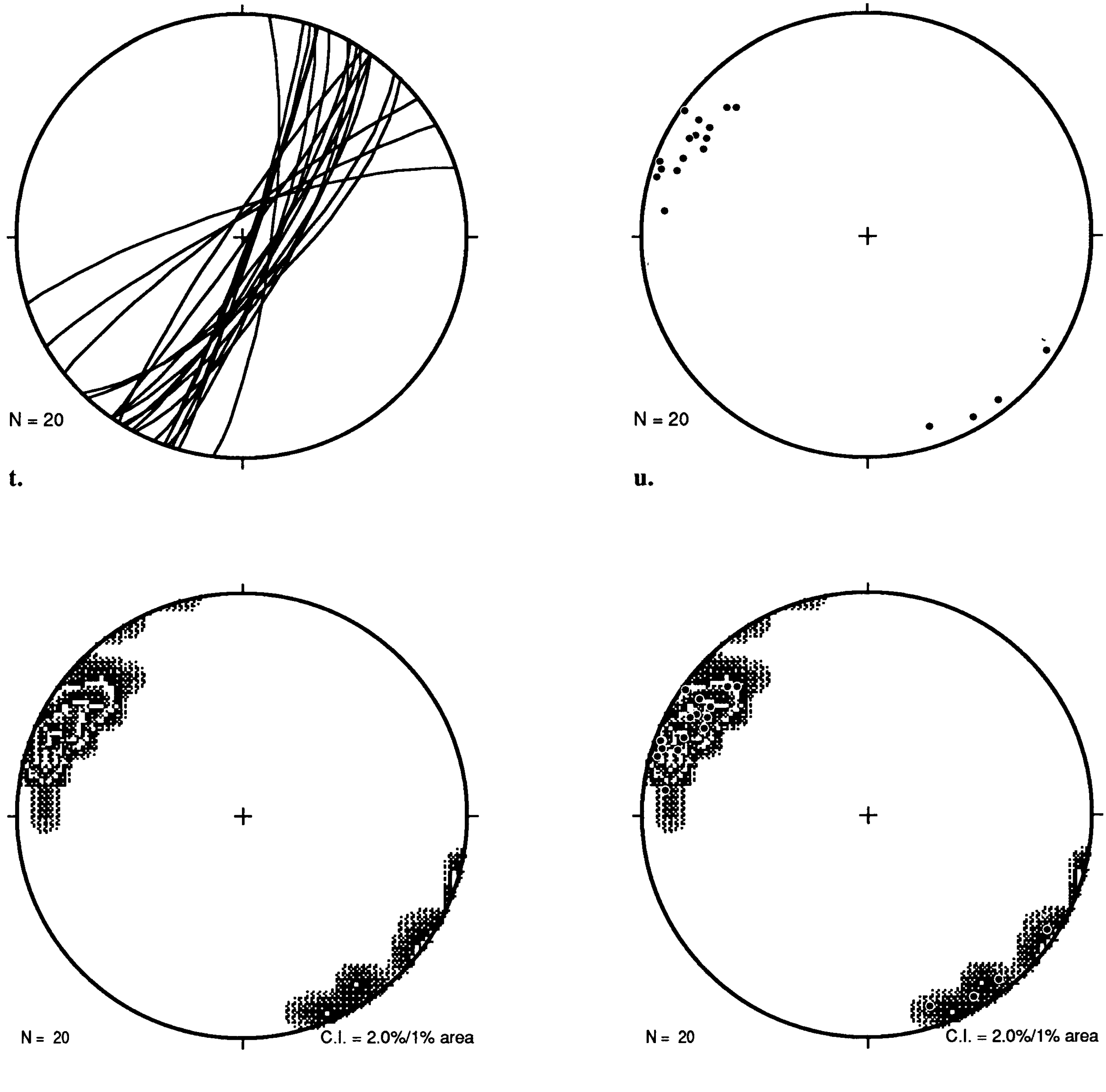



FIGURE 19. Stereoplots of dike orientations from Mt. Suess locality of Granite Harbour region. t) Great circle plot showing strike and dip of dike planes, u) scatter plot of poles to dike planes, v) contoured of poles to dike planes, and w) contour plot with poles.

# GRANITE HARBOUR - MACKAY GLACIER

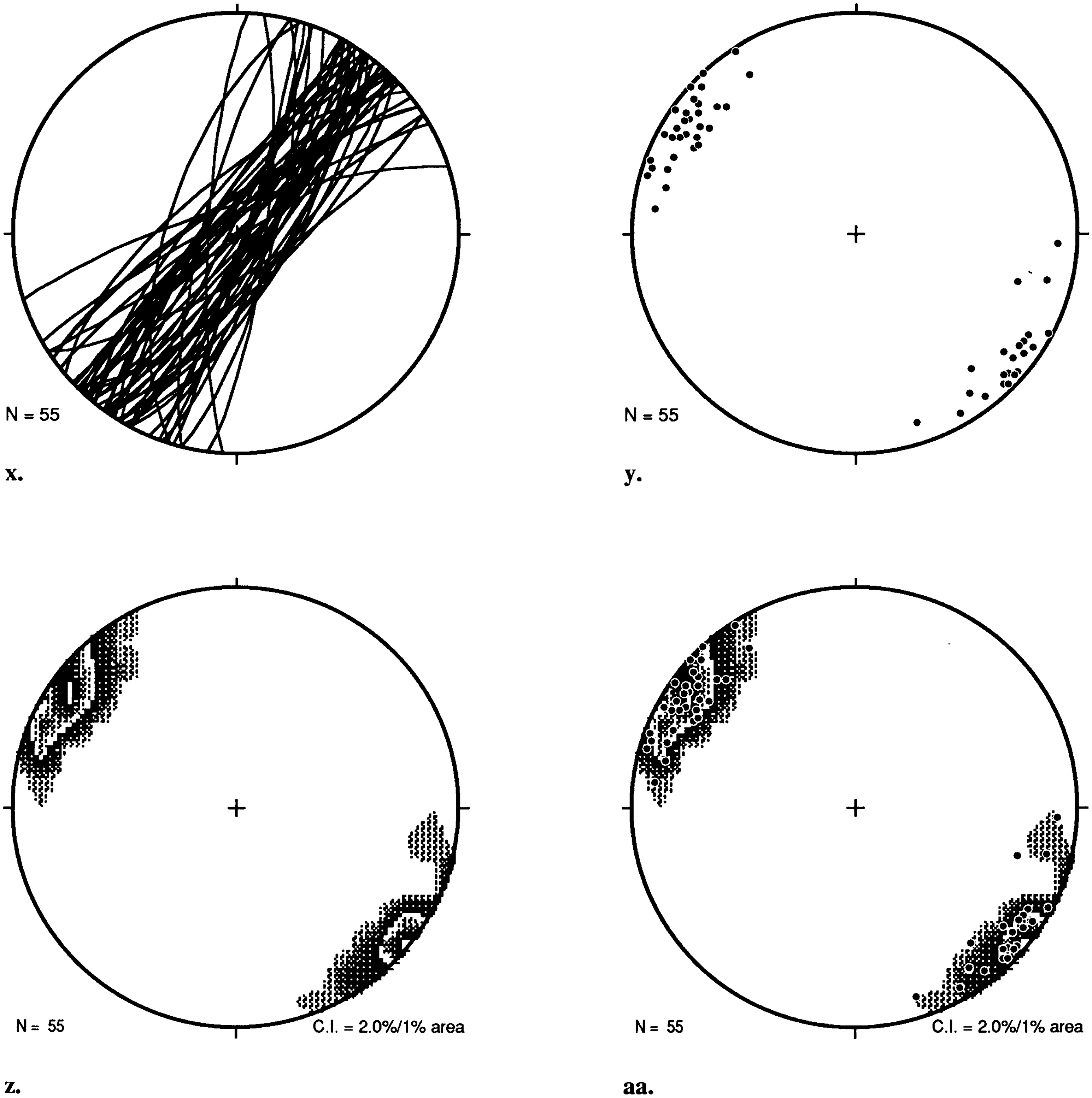



FIGURE 19. Stereoplots of dike orientations from Granite Harbour-MacKay Glacier region. x) Great circle plot showing strike and dip of dike planes, y) scatter plot of poles to dike planes, z) contoured of poles to dike planes, and aa) contour plot with poles.

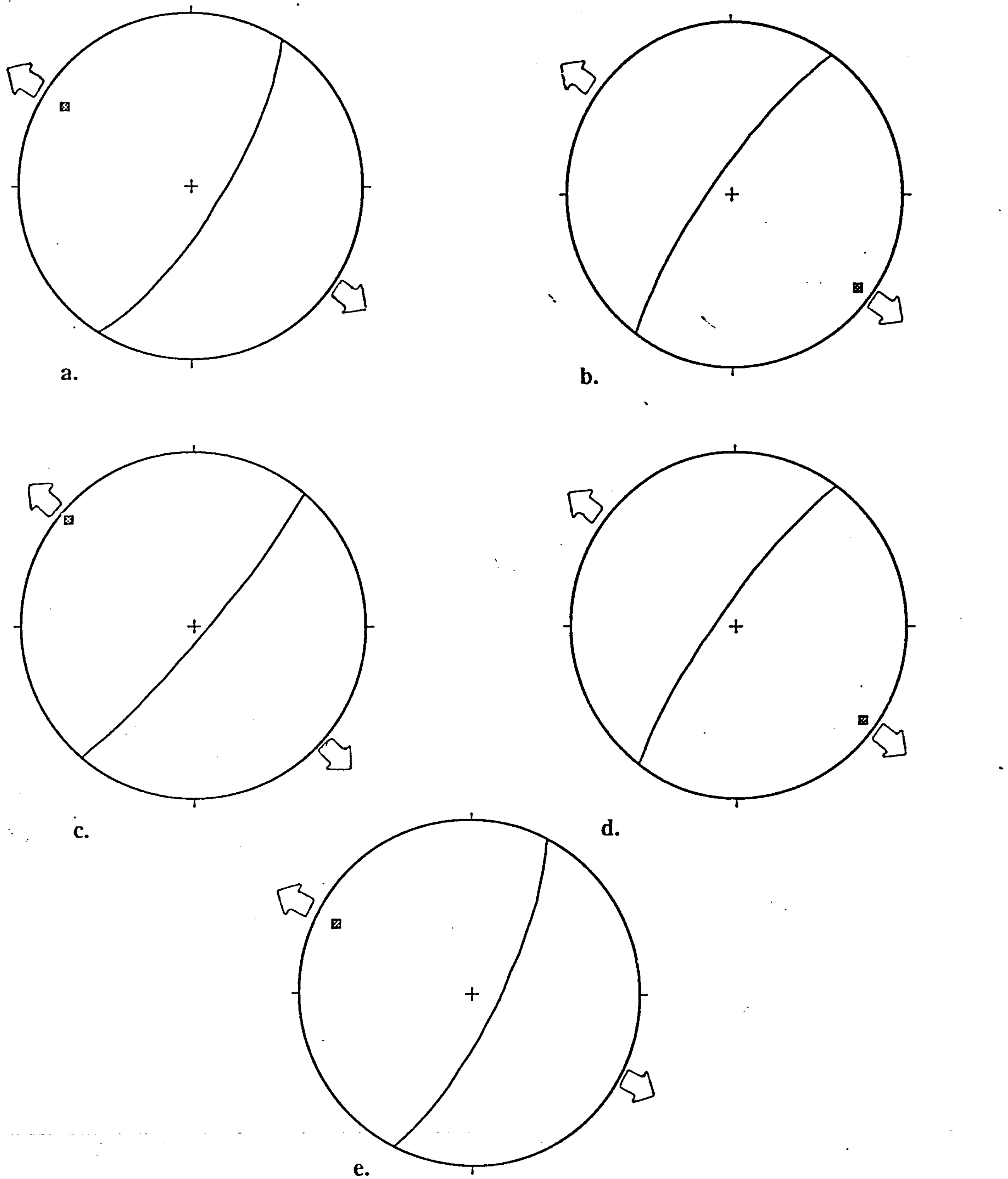



Figure 20. Stereoplots of average dike orientations and extension direction from 5 localities of Granite Harbour region. a) Avalanche Bay, average orientation N32E, 76E & extension direction 304-124 degrees. b) Discovery Bluffs/Cape Geology, average orientation N216E, 81W & extension direction 127-307 degrees. c) First View Point, average orientation S40E, 84E & extension direction 311-131 degrees. d) Minnehaha Ice Falls, average orientation N218E, 82W & extension direction 128-308 degrees. e) Mt. Suess, average orientation S27E, 77E & extension direction 207-117 degrees.

shallow westerly dip compared to the majority's easterly dip. Only 2 orientations were taken at First View Point so it was compiled with the other sets. The remaining 3 localities all show a steep dip east (with the exception of Mt. Suess' easterly) and show about 5-8 orientations each which deviates from a well-defined northeast trend. The Granite Harbour and Mackay Glacier region show a dominating northeast trend which shares those of the entire McMurdo Sound sector. Compilation of orientations from the various localities are also represented in Figure 19 illustrating all the similar northeast trends throughout the region.

## Relations Between Dike Swarms and Structures in Host Rocks

Dike occurrences throughout the McMurdo Sound sector predominantly indicate post-tectonic emplacement through observations of cross-cutting relations with pre-, syn-, and post-tectonic granites. Only augite-biotite lamprophyres have evidence of syn-tectonic activity, being characterized by high levels of deformation and moderate metamorphism with well developed schistosity parallel to that of host rocks (Blank et al., 1963; Haskell et al., 1965). Gunn and Warren (1962) also observed the lack of chilled margins in syn-tectonic granodiorites where these quartzo-feldspathic lamprophyres intruded, indicating dike intrusion occurred while the granodiorite mass was still hot and deforming. Hornblende lamprophyres and other dike suites which intrude older augite-biotite lamprophyres display only moderate alteration and no appreciable amount of metamorphism, indicative of their post-tectonic nature (Blank et al., 1963; Haskell et al., 1965; Gunn and Warren, 1962; Skinner, 1983).

At Nussbaum Riegel in the Taylor Valley, Haskell et al. (1965) reported lamprophyre dikes that were dextrally offset by faults (up to 100 feet) that were intruded by later, younger lamprophyres. Gunn and Warren (1962) also reported in the Nussbaum Riegel region post-tectonic, east-striking dike intrusions that cut normal to folded bedding and schistosity. Observations of dike swarms at several localities show trends parallel to transverse joint systems in underlying marbles (Gunn and Warren, 1962). These pre-existing joint systems and areas of rock weakness may have locally guided the dike emplacement. On a regional extent however, as depicted in Figure 17 and Plate 1, a consistent northeast dike swarm trend throughout the McMurdo Sound sector indicates that dikes propagated their own fractures.

# DISCUSSION

## Structural Interpretation of Dike Swarms

Intruding magma must exert a higher pressure (hydraulic) than that of a minimum compressive stress in order to propagate and generate tension in the host rock. Consistent northeast dike orientations throughout most of the McMurdo Sound region would therefore indicate a northwest-southeast extensional direction. In the Granite Harbour area, extensional directions perpendicular to previously mentioned average orientations include: Avalanche Bay, 304-124 degrees; First View Point, 311-131 degrees; Discovery Bluffs/Cape Geology, 127-307 degrees; Minnehaha Ice Falls, 128-308 degrees; and Mt. Suess, 297-117 degrees (Fig. 20). Certain localities, such as the Lower Taylor Valley and Hobbs Glacier regions, however, (see Plate 1) exhibit cross-cutting dike sets of various orientations (Angino et al., 1962; Webb and McKelvey, 1959; Allen and Gibson, 1962). If cross-cutting dikes were found to be similar in age, they were either 1) indifferent to propagating in the direction of least compressive stresses or 2) experienced heterogeneous stresses. Dikes exhibiting these orientations would be poor indicators of a local paleostress direction. Only cross-cutting dike sets of different ages can reflect the evolutionary change of a paleostress field and extension direction through time. This would need to be established by further field work in the study area.

**Tectonic Models for Dike Emplacement**

Tensile stresses which generate magma hydrofractures can occur in several tectonic settings. Evidence of dike swarms cutting undeformed post-tectonic plutonic rocks (Borg et al., 1990) indicates that extensional paleostresses probably existed after the compressional deformation associated with the Ross Orogeny. Extension in the overriding plate above a convergent Antarctic margin could indicate initiation of rifting resulting from subduction-related stresses. In this case one would expect extension perpendicular to the East Antarctic margin. However, if northwest structural trends indicate the trend of the convergent margin, then the extension direction indicated by the dikes is at a high angle to the margin, rather than parallel to it, arguing against this model. Evidence of subduction-related mantle-derived magmas dated at 500 m.y. on the other hand (Borg et al., 1990) supports the existence of a subduction zone along the East Antarctic margin during Early Ordovician time (Fig. 3). Further investigations of both the supporting and arguing evidence would be needed to be carried out in order to explain the exsistence or not of this model. A possible rifting event however, probably ceased when subduction and subduction-related stresses terminated.

Large-scale lateral strike-slip movement and accretion of suspect tectonostratigraphic terranes is an alternative model for producing magma-induced extensional fractures and dike emplacement (Fig. 4). A dextral sense of strike-slip motion along the East Antarctic margin would translate 'outboard' terranes northward and create a compressional stress regime 'inboard' on the craton. This resulting stress field would induce a component of tension normal to the least compressive stresses in a northwesterly-southeasterly direction and promote the generation of tensile fractures (and subsequent advance of magma), forming dikes. The regional northeast trend of dikes observed in the Transantarctic Mountains along with evidence of juxtaposed different stratigraphic sequences (Rowell and Rees, 1989; Borg et al., 1990) supports this tectonic model of dike emplacement.

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